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JOURNAL OF THE AERONAUTICAL SCIENCES

Volume 2 JULY, 1935 Number 4

Proceedings
Twenty-Third Wilbur Wright Memorial Lecture and Conversazione
London, May 30, 1935

Reprinted through the Courtesy of the Royal Aeronautical Society

A CONVERSAZIONE was held by the Royal Aeronautical Society at the Science Museum, South Kensington, London, on Thursday, May 30, 1935. Six hundred members and guests attended to hear the Wilbur Wright Memorial Lecture by Mr. Donald W. Douglas, President of the Institute of the Aeronautical Sciences.

The President, Lt. Col. J. T. C. Moore-Brabazon, presided. He read the following message:

"Institute of Aeronautical Sciences extends a hand across the sea in cordial greetings to the Royal Aeronautical Society on occasion of President Douglas delivering the Wilbur Wright Lecture. To have the President of our three year old Society honoured by the oldest aeronautical group is a distinction appreciated here.
Lester D. Gardner."

Continuing, the President said he had taken the opportunity a few days previously of sending the following telegram to Mr. Orville Wright—an old friend of the Society:

"On Thursday next your countryman D. W. Douglas will deliver the Twenty-Third Wilbur Wright Memorial Lecture on the Progress of the Air Liner before the Royal Aeronautical Society. I send you on behalf of the Council and Members a message of cordial goodwill and appreciation of the pioneering work of your distinguished brother and yourself, work which is recalled each year on this occasion with growing admiration of the way in which you met and overcame the fundamental problems of the first power driven controlled flight in a heavier-than-air craft.
Moore-Brabazon
President."

The following reply had been received:

"Greetings to the Council and Members assembled for the Twenty-Third Wilbur Wright Memorial Lecture. Development of the air liner has been an outstanding feature in American aviation. Mr. Douglas' part in this has been second to none. We are proud of him.
Orville Wright."

The President, before calling upon Mr. Douglas to deliver the Wilbur Wright Lecture, expressed appreciation of the kind permission of Col. E. E. B. Mackintosh, Director of the Science Museum, to hold this meeting—which was the most important the Society held during the year—in this particular building in such close association with what must be by far the most important historical machine that aviation had ever known—the actual first machine to fly. Sitting there as they did in remembrance and looking at that amazing contraption of wood, metal and fabric it was perhaps difficult to realize that it was only 30 years ago that that machine was built but already it had changed the outlook of many things in the world and of the great responsibility of all mankind to flight. It was indeed the wish not only of us in this country but the wish of the whole world that we should be worthy of what the Wrights did and not to reduce the whole thing to nothing else than armaments. That evening they were honouring the Wrights by listening to one who

had devoted his whole life and brain to the development of fast civil aircraft. The work which Mr. Douglas had done had had a very profound effect upon the whole of aviation throughout the world. His genius and his design had upset some of those people who although not in aviation were a conservative type. It was perhaps only right that it was arranged to have this Lecture on Ascension Day; it was particularly appropriate.

Referring to the printed lecture (which follows these proceedings), and which had been distributed among the members, the President said that Mr. Douglas had sent this along in his usual quiet way and it was very scientific and full of curves, the sort of thing which those in the Royal Aeronautical Society thoroughly enjoyed and took to bed to read (laughter). The Wright Lecture was intended to be of a more popular type and therefore they had asked Mr. Douglas if he could turn his more technical lecture into a popular form. Mr. Douglas had consented to do that and instead of reading the printed technical lecture he would give a talk and show a film dealing with the development of civil aviation in America, more particularly with regard to his own activities there.

Mr. Donald W. Douglas

I consider it a great honor to be here before you tonight on such an outstanding occasion and to be able to join with your Society in again honoring the memory of Wilbur Wright. I bring to the members of the Royal Aeronautical Society the hearty and cordial greetings of the Institute of the Aeronautical Sciences—our younger but similar association in America. Tonight I am not going to talk directly on the technical paper which I have submitted to you but rather on the general subject of the developments in the air transport field in America. I not only feel that this might be less trying to many of you but I am hopeful that the moving picture film I am about to have shown to you will so engross your attention that any defects in my talk will be unnoticed.

The stock market must be given some credit for the rapid increase in air travel in the early phase, since the money secured by the industry made possible a great expansion of facilities. In this period, the development was most rapid in the ground organization of our large air carriers and in the navigational facilities supplied, in the main, by our constructive Department of Commerce. Thus, by, we will say 1930, and in spite of an already hesitant tone in general business in America, the stage was set for the really rapid technological progress of the past five years.

It seems to me it has been the golden age of aeronautics for us—although not an age for gold in America! An alert and ambitious military technical personnel played its part in accelerating the use of brains by our designers. A growing competition among our air lines spurred the development of faster and safer air liners. A need on the part of the manufacturers for a broader market for their products and an ability, represented in favorable balance sheets, to seek this with newer and better types, both military and civilian, added to the activity of this field. Early attempts at really fast airplanes, such as the original and successful Lockheed, pointed the way to others as to what might be done. But even beyond all this, and most certainly marking the time as one of real accomplishment, has been the fact that all agencies concerned in and contributing to aviation have been most alert, cooperative and constructive. Our engines have been developing at a pace to permit the airplane designer to raise his sights from time to time. Our instrument and radio people have aided tremendously by furnishing us with the means to fly in bad weather. Propeller makers have been most helpful and, in fact, I can say that the development of the variable pitch propeller to the point it has reached today, is probably the most fundamentally important development of this period. Without it many of our present air liners would be impracticable.

The thought was developed that speed in the air was but one function to be solved in the solution of the equation of a successful ship. Speed of inspection and maintenance during fuelling stops, and studies to cut the time required to make replacements, were given great consideration. Safety was a factor which, of course, had to be developed to the utmost possible. Here we were furnished aid by the engine maker, the instrument people, the propeller designer and the wind tunnel and research agencies of our government and of our technical institutions. Flying, as our major air lines do, over great distances across high country in many places and through or over weather of the worst at times and continuation of flight at any point with one of our two engines stopped, was the prime requisite we had always before us in our design. Comfort was studied with care, and sound engineers developed efficient and practical methods of eliminating the formerly disagreeable and tiring noise of air transport. Heating and ventilation comparable to that found in modern buildings was effected after the aid of related industries was obtained.

I have spoken only about land transportation. The film will show you flying views of the latest and finest of our flying boats—the Sikorsky and Martin. These have been brought out by those two great concerns working closely with Pan-American Airways. They, in the Ford-Fokker era of land plane transportation, started their ambitious and highly successful foreign air lines with flying boats largely developed from naval boats. These latest pieces of equipment represent the last word as we know it in America for the safe and successful operation of overseas transport. With their four great engines it is difficult to imagine a flight failure due to engine trouble. Sea-worthy hulls of large size seem adequate to permit of safe landings under all conditions likely to be met. Comfort is even better served in these commodious hulls than in the smaller bodies of our land planes.

The story of the development of modern air liners would not be complete if we did not give credit to the effect of greater technical thought as applied to the flight of the air liner, rather than just to the design of the machines. Formerly the aeronautical engineer had completed his work when the final flight tests of his airplane were completed. From then on it was up to the pilot who while vitally concerned with the proper speed and altitude at which to fly was not informed completely as to just what factors determined his best course. With the idea of realizing the ultimate in air line operations from the standpoint of speed and economy, many engineers and engineering pilots have necessarily collaborated. Results of their work in theory and flight tests have been made available to all and in such form that they are of great practical value and aid. Dr. Oswald of our staff and Pilot Eddie Allen have blazed the path along these lines and

further valuable information is being gathered by others inspired by this work. As can be seen from what I have said we are only just learning to utilize the machine that we have developed. This brings me to the thought of the future development. What lines do we wish to develop along; speed, safety, comfort, size, efficiency? Speed to its ultimate, most certainly. Future development must include the development of all the speed possibilities in air travel consistent with other necessary considerations. I believe we should be cruising at 300 miles per hour in another ten years. Stratosphere or sub-stratosphere flight while not to be developed necessarily primarily for speed, may open up avenues of development now not clear to us. Better utilization of slow landing devices will undoubtedly give us our next measurable increase in practical cruising speeds. There is undoubtedly some room for increases in overall aerodynamic efficiency. Possibly some expectations of somewhat better propulsive efficiencies is sound.

What of the development towards more safety? We must admit that while great strides have been made in this direction more can be and must be done. We can reasonably expect to continue to improve the reliability of our engines, instruments, radio, plumbing and other vital gadgets but at the moment we can only visualize a general betterment in the airplane itself by such changes as a 4-engined transport capable of flying on any two engines, rather than twin-engine airplanes. It seems at the moment that the most important advance in safety that we should be concerned with is in better protection against icing up, against electrical storms, and in better development of blind flying and blind landing facilities. The icing problem is partially but inadequately solved at the moment. Its better solution may be mechanical and may also be along the line of greater altitude capabilities of the air liner. Hand in hand with this solution for icing goes the possibility that protection against dangerous electrical conditions may lie mainly in high altitude flight. Comfort development, certainly, is an open field and includes the problem not only of comfort but sustentation of life at the high altitudes at which we may soon wish to fly. Pressure cabins and/or free oxygen in the cabins are both being experimented with today. Our air lines are working diligently with our designers on these points and we look with confidence to some solution soon.

Our future developments from the standpoint of size seem, except in the case of transoceanic flying boats, to be controlled by traffic and comfort. Intrinsically one of the advantages of air transport is its flexibility so it would seem that size, beyond an efficient point from a structural standpoint and an economic one, is not to be expected to show any great change. Efficiency we must certainly hope to continue to improve, in order that air transport may be able to show an operating profit without depending on any subsidy. This will be improved by better pay-load percentages, lower first costs and lower maintenance charges. Already in America we find the operating costs of the modern ships quite markedly lower than the older and slower planes. Therefore, we need not fear that even with our speed development we shall cease decreasing costs.

It seems to me that aviation is so concerned with ground facilities of such a world-wide and international scope that the most important developments will come when we find means to more completely cooperate as nations. Also it appears that so much time and money is wasted because of the duplication of the same experiments in different countries that something constructive should be considered at the present time. From this point of view military aviation seems to be a factor deterrent to more rapid and less costly progress. Why, however, can we not hope to take certain general aviation problems that do not involve anything intrinsically military, and allot them among the major nations—certain problems to one nation with more experience on a certain phase and certain problems to another? A complete interchange of the knowledge resulting would then follow. Surely this is possible and if it is, the aviation industry instead of being a potential breeder of war with its increasingly dangerous weapon, might become an agent in spreading understanding. I offer these last thoughts humbly and in the belief that engineers and scientists such as form the membership of the Royal Aeronautical Society, are most fully able to grasp the possibilities. A glorious future lies before aviation. Its development has only just commenced. May I hope that those interested in it here will believe that we in America extend to you our fellowship and promise of full cooperation for the common good.

Mr. C. R. Fairey in proposing a vote of thanks to Mr. Douglas said they had listened to a very vivid, practical and interesting talk but they all had in their hands the print of an equally interesting and even more important lecture—since in that Mr. Douglas proved the high speed in aviation could be obtained without any loss of economy, of safety, or of comfort, as the aircraft on the world's airways had already proved. It was to be hoped that in the hands of our designers this lecture would have some effects on the future of British air transport. If it led to the fact that we never heard again of that strange doctrine under the headline of "the fallacy of speed" it would have done something, although he was never quite clear himself as to whether the protagonists of that amazing doctrine were out to prove that airplanes ought not to go fast or to apologize because they did not do so (laughter). After all, the basic ratio, L/D, had a commercial as well as a technical significance for aeronautical engineers. L was the income and D represented the out-goings and anything we could do to improve L/D was all to the good of commercial aviation and Mr. Douglas had certainly done that.

Everybody was grateful to Mr. Douglas for having travelled the long distance he had to deliver this lecture and also for the trouble he had taken in preparing it, and further, for giving them the opportunity of meeting him personally.

The vote of thanks was carried with hearty enthusiasm.

Mr. Douglas, acknowledging the vote of thanks, said the pleasure he had in coming to England to give this lecture had been enhanced by the great kindness shown to him and the indication that had been given that those who had listened to him had, at any rate, enjoyed the lecture to some extent.

The Developments and Reliability of the Modern Multi-Engine Air Liner With Special Reference to Multi-Engine Airplanes After Engine Failure*

DONALD W. DOUGLAS, *President of the Institute of Aeronautical Sciences*

Reprinted Through the Courtesy of the Royal Aeronautical Society

FOUR essential features are generally required of any form of transportation: Speed, safety, comfort and economy. The airplane must compete with other forms of transportation and with other airplanes. The greater speed of aircraft travel justifies a certain increase in cost. The newer transport airplanes are comparable with, if not superior to, other means of transportation. Safety is of special importance, and improvement in this direction demands the airplane designer's best efforts.

Safety and Reliability

Statistics show that the foremost cause of accident is still the forced landing. The multi-engine airplane, capable of flying with one or more engines not operating, is the direct answer to the dangers of an engine failure. It is quite apparent, however, that for an airplane that is not capable of flying with one engine dead the risk increases with the number of engines installed. Hence, from the standpoint of forced landings, it is not desirable that an airplane be multi-engine unless it can maintain altitude over any portion of the air line with at least one engine dead. Furthermore, the risk increases with the number of remaining engines needed to maintain the required altitude. In general, therefore, the greatest safety is obtained from—

(1) The largest number of engines that can be cut out without the ceiling of the airplane falling below a required value;

(2) The smallest number of engines on which the airplane can maintain this given altitude.

For airplanes equipped with from one to four engines, it follows that the order of safety is according to the list following.

(*a*) Four-engine airplane requiring 1 engine to maintain given altitude.

(*b*) Three-engine airplane requiring 1 engine to maintain given altitude.

(*c*) Four-engine airplane requiring 2 engines to maintain given altitude.

(*d*) Two-engine airplane requiring 1 engine to maintain given altitude.

(*e*) Three-engine airplane requiring 2 engines to maintain given altitude.

(*f*) Four-engine airplane requiring 3 engines to maintain given altitude.

(*g*) One-engine airplane requiring 1 engine to maintain given altitude.

(*h*) Two-engine airplane requiring 2 engines to maintain given altitude.

(*i*) Three-engine airplane requiring 3 engines to maintain given altitude.

(*j*) Four-engine airplane requiring 4 engines to maintain given altitude.

Reliability and safety, however, depend upon other factors. These can generally be classified as the airline over which the airplane operates, and the aerodynamic design of the airplane. The airplane designer has control of reliability in so far as he is able to modify the multi-engine design to enable it to complete its flight over the necessary terrain after engine failure.

While safety probably requires only that the airplane be able to fly to the nearest landing field with one engine out of operation, reliability of multi-engine airplanes indicates more properly the possibility of carrying on flight to the original destination without hazard and discomfort. The length of trip, altitude required, amount of fuel load that can be disposed of, percentage of power required to maintain flight, control and performance of the airplane—all these considerations must be studied before a figure of merit can be assigned to any multi-engine airplane.

The favorable position in the above table of

* The author wishes particularly to acknowledge the co-operation of Dr. W. Bailey Oswald in the preparation of the paper, and the generous co-operation of the various companies, testing agencies, and individuals.

the two-engine airplane capable of single-engine flight is quite interesting. This type appears to offer a very valuable combination of safety and economy. Since, for a given power, the airplane drag, weight and cost increase with the number of engines, the economy of these types with more than two engines is inferior to that of the bimotor.

Where the terrain and trip length are such as to require carrying the full cargo load for long distances after the failure of an engine, and where the added reliability of continued operation after the failure of two engines is desired, the four-engine airplane appears to be most favorable. The cases (*a*) and (*b*), showing highest reliability in the table, are believed, at least for the present, to be practically unattainable with maintenance of any considerable cargo load.

Performance and Control

The most usual misconception associated with multi-engine airplanes is that the reliability increases indiscriminately with the number of engines, which, of course, is far from fact. Unless the airplane can maintain the necessary altitude under proper control after engine failure, the reliability decreases with the number of engines. It is possible, for example, through aerodynamic design of the airplane, particularly regarding the wing and control surfaces, to make a two-engine airplane more desirable than one with more engines which is not especially designed for operation after engine failure.

The performance after engine failure is more critically affected by the various characteristics of the airplane and propulsive unit than is the normal performance, principally because of the low excess of power. While this critical nature of the performance is generally found to be unfavorable, it can be of assistance to the designer because small favorable changes in the design characteristics give large improvements in performance.

The design of airplanes for operation after failure of one or more engines is definitely a critical problem. The engineer is adequately rewarded for careful design as surely as he is penalized for merely normal design of a multi-engine airplane intended for operation after engine failure.

It is evident that the most important performance characteristic after engine failure is the absolute ceiling. Rate of climb at lower altitudes will, in general, improve as the ceiling improves. Maximum velocity and cruising speed are relatively unimportant. Safety and reliability demand that the airplane be able to fly successfully over all obstacles in the line of operation.

Because of the direct relation between safety and reliability of operation and flight of multi-engine aircraft on partial engine power, a prediction of such performance is of considerable interest. The present report develops a rapid parameter and chart method for determining such performance. The various contributing factors have been investigated and adjusted to check such flight test data as are available. The method is believed to produce results comparable in accuracy to flight test measurements, and has the advantages of explicitness and rapidity inherent in a chart method.

TABLE I. *Flight test on attitude of bimotor airplane in single-engine flight. Airplane—Douglas XB-7.* Gross weight 9,208 lbs.

	Test A Normal level flight. Zero bank. Engines wide open. R. Eng. & L. Eng.	Test 1. Single-engine flight at zero bank. R. Eng.	Test 1. L. Eng.	Test 2. Single-engine flight at zero yaw. R. Eng.	Test 2. L. Eng.	Test 3. Single-engine flight at increased angle of bank. R. Eng.	Test 3. L. Eng.
Indicated air speed	156	104	102	104	102	104	102
R.P.M., right engine	2,450	2,120	1,100	2,120	1,100	2,120	1,050
R.P.M., left engine	2,400	1,100	2,080	1,100	2,080	1,100	2,080
Yaw meter reading	+15° to −15° (vibrating)	3° R	2° L	0°	0°	2° L	4° R
Bank indicator	0°	0°	0°	1½° R	1½° L	5° R	4½° L
Rudder angle	1° R	13° R	12½° L	12° R	12° L	11° R	12° L
Rudder flap angle	0°	Full L	Full R	Full L	Full R	Full L	Full R
Aileron angle	1° R	1° R	1° R	2° R	1° R	3° R	0°

Attitude of Flight

The question naturally arises regarding the attitude of a multi-engine airplane when only part of its engines is operating, and the effect of such attitude upon the performance characteristics. Flight tests made in this connection have served to bring out some interesting comparisons.

Three characteristic attitudes will be described, there being, of course, an infinite number of gradations between them. With adequate control, the pilot will be able to choose the most efficient attitude; whereas, with inadequate control, the airplane will assume one less desirable. The three cases are illustrated in Fig. 1, and the flight test data are tabulated in Table I. The three attitudes of flight are as follows:

1. Zero angle of bank (with skid)

It will be seen from Fig. 1a that the thrust and propeller set up a moment which is balanced by the rudder. The rudder side force is, in turn, balanced by the side force on the body produced by the skid. This attitude, which requires a large rudder throw, since the skid is against the rudder angle, is not always possible of attainment if control forces are too great or if the rudder is of insufficient power. Additional drag above that in normal flight arises from the idling propeller, rudder, and body in yaw. Secondary moments and drags arise from the rudder force, moment of body, drag due to aileron angle, and additional induced drag caused by unsymmetrical airflow over the wing. The flight test results in Table I show at zero angle of bank, 2.5° average angle of skid and 11.8° average rudder angle. Ailerons were in neutral.

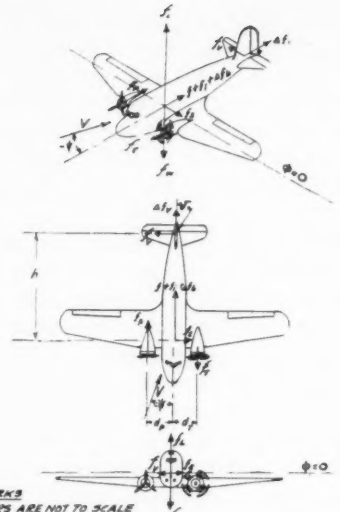
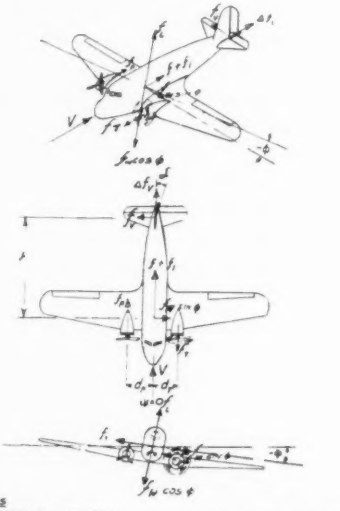

REMARKS
1 VECTORS ARE NOT TO SCALE
2 FORCES ARE SHOWN IN THE DIRECTION OF BODY AXES
3 COSINE ψ IS ASSUMED = 1
4 SIDE FORCE ON NACELLES IS NEGLECTED
5 SECONDARY MOMENTS NOT SHOWN
6 NORMAL ANGLE OF ATTACK NOT SHOWN
7 IDLING PROPELLER ACTUALLY DOES NOT STOP UNLESS LOCKED
EQUILIBRIUM EQUATIONS

FIG 1a EQUILIBRIUM OF FORCES ON A BI-MOTORED AIRPLANE IN SINGLE ENGINE FLIGHT ATTITUDE (1) ZERO ANGLE OF BANK (WITH SKID)

2. Zero angle of yaw (with bank)

In this case, as seen from Fig. 1b, the rudder side force is balanced by a component of the weight arising from the angle of bank. Calculations indicate that this angle is usually of the order of about 1° to 3°. This attitude, like attitude 1, is not possible unless the rudder is of sufficient size and the control forces sufficiently low to permit the throw required. The rudder is responsible for all of the balancing moment,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EQUILIBRIUM EQUATIONS

FIG 1b EQUILIBRIUM OF FORCES ON A BI-MOTORED AIRPLANE IN SINGLE ENGINE FLIGHT ATTITUDE (2) ZERO ANGLE OF YAW (WITH BANK)

since the angle of yaw is zero. Additional drag arises principally from the idling propeller and vertical tail surface. Secondary moments and drag forces are present as before. The flight test results show at zero yaw an angle of bank of 1.5°, a rudder angle of 11°, and a slight aileron angle of 0.5° holding the lower wing down. The rudder angle is less than that for attitude 1. since the surface acts in air at zero angle of yaw and not in a skid against the angle.

3. Yaw into angle of bank (with side-slip)

This attitude, shown in Fig. 1c, results when there is insufficient control to attain either of the former. The airplane is side-slipped at a large angle of bank until the fin produces the balancing force needed. The side-slip develops a side force on the body which does not contribute to balancing the thrust moment, but does require additional bank in order that the weight component may balance both this body force and the side force on the vertical surface. Additional drag arises from the idling propeller, body at yaw, and the vertical surface. Secondary moments and drags are, no doubt, greatest for this case since angles of bank and yaw, and the side forces, are here greatest. The flight test data show a mean 3.0° angle of side-slip (yaw), 4.8° angle of bank, rudder angle of 10.5°, and average aileron angle of 0.5° holding the airplane into the bank. The flight test was a very mild case of attitude 3 (yaw into angle of bank) since the rudder was held hard over. It is quite apparent that with rudder free the angles of bank and yaw would increase greatly until the performance would be seriously affected.

This study of the various states of equilibrium possible brings to light several interesting facts. The attitude of the airplane in bank and yaw depends upon the unbalanced moment and the amount of rudder control that the pilot can exert and maintain with comfort. Excessive rudder control would permit flight with an outside skid and bank away from the offset thrust, while insufficient rudder control would require a large side-slip and bank toward the offset thrust. There appears to be no necessity to reach the attitude of zero bank, for zero yaw is probably the optimum from the standpoint of drag. Fortunately there seems to be little loss for small variations on either side of the zero yaw case, but extreme deficiency of rudder control would certainly lead to decreased performance resulting from high drag at the large angles of yaw and bank required.

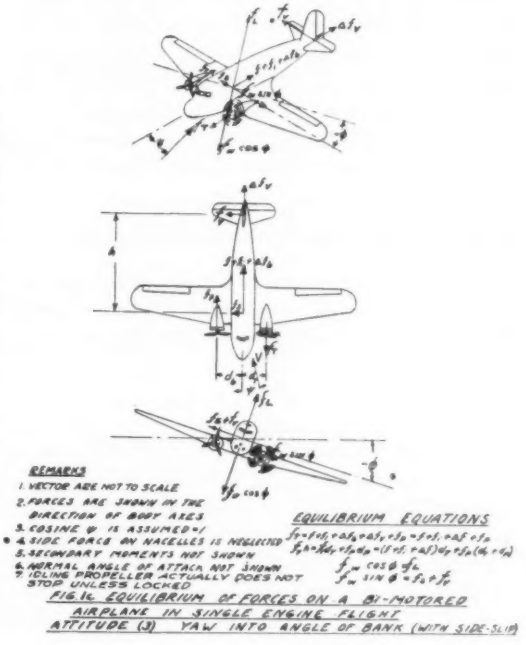

REMARKS
1. VECTOR ARE NOT TO SCALE
2. FORCES ARE SHOWN IN THE DIRECTION OF BODY AXES
3. COSINE Ψ IS ASSUMED = 1
4. SIDE FORCE ON NACELLES IS NEGLECTED
5. SECONDARY MOMENTS NOT SHOWN
6. NORMAL ANGLE OF ATTACK NOT SHOWN
7. IDLING PROPELLER ACTUALLY DOES NOT STOP UNLESS LOCKED
EQUILIBRIUM EQUATIONS

FIG. 1c. EQUILIBRIUM OF FORCES ON A BI-MOTORED AIRPLANE IN SINGLE ENGINE FLIGHT ATTITUDE (3) YAW INTO ANGLE OF BANK (WITH SIDE-SLIP)

Performance Equations

The following analysis is based on the general parameter method of performance calculation developed in Reference 1 for airplanes with unsupercharged engines, and expanded in Reference 2 to include airplanes with supercharged engines. For an airplane operating under normal conditions, the parameters are three loadings and the major performance parameter derived from them, which are defined in the usual American and English engineering units as follows:

$$\left.\begin{aligned}
&\text{Parasite loading } l_p = W/f = \frac{\text{Weight (lb.)}}{\text{Equivalent parasite area (sq. ft.)} = C_{D_p} S} \\
&\text{Span loading } l_s = W/e(kb)^2 = \frac{\text{Weight (lb.)}}{\text{Airplane efficiency factor} \times \text{equivalent monoplane span}^2 \text{ (ft.}^2\text{)}} \\
&\text{Thrust horsepower loading } l_t = W/\text{b.hp.}_m \eta_m = \frac{\text{Weight (lb.)}}{\text{Design max. brake horsepower} \times \text{design max. propulsive efficiency}} \\
&\text{Major performance parameter } -\lambda = l_s l_t^{4/3}/l_p^{\frac{1}{3}}.
\end{aligned}\right\} \quad (1)$$

The airplane efficiency factor (e) depends upon interference drag, variation from elliptical lift distribution, and variation of parasite drag with angle of attack, and varies from about 0.70 to 1.00. All the principal performance characteristics can be obtained from these parameters. Charts for this purpose are found in Reference 1.

Parameters for Flight after Engine Failure

For the performance after failure of one or more engines, it seems probable that all of these parameters are modified. The following development takes into account variations in all three of the parameters due to engine failure. It is shown later, however, that for practical purposes it is justifiable to assume that only two are changed. When sufficient data are available on maximum velocity, maximum rate of climb, and ceiling of airplanes operating with partial engine failure, the changes in the three basic parameters can be determined. Since ceilings constitute the only reliable data now available in sufficient quantity, the variations in the three parameters are somewhat uncertain, hence the final simplification given later.

Defining, for the general development,

$$\left.\begin{aligned}
x &= \frac{\text{Engines in operation}}{\text{Total number of engines}} \\
y &= \frac{\text{Airplane efficiency factor after engine failure}}{\text{Normal airplane efficiency factor}} = e_x/e \\
z &= \frac{\text{Equivalent parasite area after engine failure}}{\text{Normal equivalent parasite area}} = f_x/f
\end{aligned}\right\} \quad (2)$$

the performance parameters become

$$\left.\begin{aligned}
l_{s_x} &= l_s/y \\
l_{p_x} &= l_p/z \\
l_{t_x} &= l_t/xT_{v_x} \\
\Lambda_x &= \Lambda z^{\frac{1}{3}}/y(xT_{v_x})^{4/3}
\end{aligned}\right\} \quad (3)$$

For any propulsive unit, T_{v_x} is the ratio of design thrust horsepower at maximum reduced-power velocity to the value at normal high speed. T_v is a function of the velocity ratio R_v, and is shown for a peak efficiency design setting of the propeller in Fig. 2. The general effect of engine failure on thrust horsepower available and required is shown on this figure. It is assumed that for the remaining engines the drop-off in thrust horsepower available with velocity follows the normal variation. This is justified by the fact that best operation is obtained at or near zero yaw, hence the propeller is acting at or near its usual angle to the wind. Furthermore, all available information seems to indicate that the propulsive efficiency and T_v function are not appreciably affected by lateral inclination of the thrust axis. The vertical inclination will, of course, vary in the usual manner with velocity.

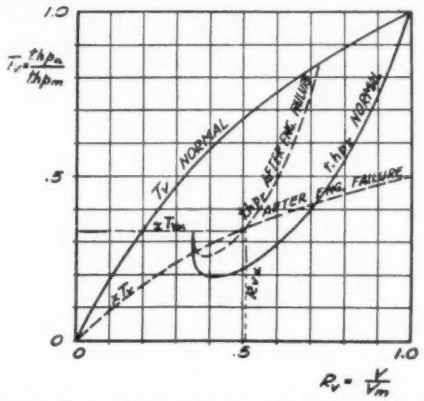


FIG. 2 VARIATION OF FULL THROTTLE THRUST HORSEPOWER AVAILABLE WITH VELOCITY. THE GENERAL EFFECT OF FLIGHT AFTER ENGINE FAILURE UPON THRUST HORSEPOWER AVAILABLE AND REQUIRED IS ILLUSTRATED

General Equation

In Reference 1, the maximum velocity is shown to be given in terms of engineering parameters by the following expression:

$$\Lambda = 52.8(l_s l_t / V_m)(1-0.332 l_s l_t / V_m)^{\frac{1}{2}} = 52.8\Gamma(1-0.332\Gamma)^{\frac{1}{2}}, \quad (4)$$

where V_m = design maximum velocity in miles per hour,

$$\Gamma = l_s l_t / V_m.$$

Substituting the parameters of Eq. (3) for operation with engine failure into Eq. (4), we obtain

$$\Lambda_z = 52.8(l_{s_z} l_{t_z} / V_{m_z})(1-0.332 l_{s_z} l_{t_z} / V_{m_z})^{\frac{1}{2}}. \quad (5)$$

Upon detailed substitution,

$$\Lambda z^{\frac{1}{2}} / y(xT_{v_z})^{4/3} = 52.8(l_s l_t / V_m)(1/yxT_{v_z}R_{v_z}) \times [1-0.332(l_s l_t / V_m)(1/yxT_{v_z}R_{v_z})]^{\frac{1}{2}}, \quad (6)$$

where $R_{v_z} = V_{m_x} / V_m$.

Solving,

$$\Lambda = 52.8[y(xT_{v_z})^{4/3}/z^{\frac{1}{2}}](\Gamma/yxT_{v_z}R_{v_z}) \times [1-0.332(\Gamma/yxT_{v_z}R_{v_z})]^{\frac{1}{2}} \quad (7)$$

or

$$\Lambda = 52.8(\Gamma/R_{v_z})(xT_{v_z}/z)^{\frac{1}{2}} \times [1-0.332(\Gamma/yxT_{v_z}R_{v_z})]^{\frac{1}{2}}. \quad (8)$$

Transposing,

$$\Lambda^3/\Gamma^3 = 147{,}198(xT_{v_z}/zR_{v_z}^3) \times [1-0.332(\Gamma/yxT_{v_z}R_{v_z})] \quad (9)$$

or

$$\Lambda^3/147{,}198\Gamma^3 - xT_{v_z}/zR_{v_z}^3 + 0.332\Gamma/yzR_{v_z}^4 = 0. \quad (10)$$

For flight with partial engine power, x, y, z, Λ and Γ are known, assuming, of course, that the actual variations to be expected in y and z have been determined for each particular type of airplane either by flight or wind tunnel test.

Simplified Equation for Charts

In order to develop a set of charts from the general relation given in Eq. (10), it is necessary to know the increase in both induced drag and parasite drag when operating after engine failure. It is believed that the only way that these factors can be correctly established is through the analysis of flight test data. Flight test data on maximum velocity, maximum rate of climb and absolute ceiling are necessary to make the desired complete analysis. At present the only reliable data that are available on multi-engine airplanes are those comparing the normal absolute ceiling with absolute ceiling after engine failure. It is therefore possible to determine only one factor, that is, either y or z, from this single performance characteristic.

It has been assumed in the following development and in the charts that the induced drag in flight after engine failure is unchanged from that in normal operation; that is,

$$y = e_x/e = 1. \quad (11)$$

This simplification is justified for performance calculations on both rate of climb and absolute ceiling for the following reason:

At the climbing attitude of the airplane, likewise at absolute ceiling, the induced drag and the parasite drag are approximately equal. Maximum rate of climb occurs at approximately the speed for maximum lift-drag ratio of the airplane, where the parasite and induced drags are equal. The performance variation curves of Reference 1, show that the effect on rate of climb of a change in parasite drag,

calculated to give a certain difference in absolute ceiling, is approximately the same as the effect on rate of climb of a change in induced drag calculated to give a like difference in absolute ceiling. So the net effect is the same whether the necessary increase in drag is added as induced drag or parasite drag.

The assumption that all of the increase in drag is of the parasitic type gives conservative results in maximum velocity calculation, since the variation in parasite drag for a given change in absolute ceiling will have a greater effect upon the maximum velocity than would the variation in induced drag causing the same change in absolute ceiling.

In view of the limited amount of data available from flight tests, and the fact that the proper relation between absolute ceiling and rate of climb is maintained by assuming that all drag increase is parasitic, and since results on maximum velocity are somewhat conservative, it seems advisable to assume that there is no increase in induced drag and that all increases are in parasite drag.

Putting $y=1$ in Eq. (10), we obtain

$$\Lambda^3/147{,}198\Gamma^3 - xT_{v_x}/zR_{v_x}{}^3 + 0.332(\Gamma/zR_{v_x}{}^4 = 0. \quad (12)$$

This equation is used in the development of the succeeding charts. Charts are given at the end of the paper for the cases of $x=0.50$, 0.67, and 0.75, corresponding respectively to a two-engine airplane operating on one engine, a three-engine airplane operating on two engines, and a four-engine airplane operating on three engines. Other cases can easily be derived from the equations or obtained by interpolation from the charts given in this paper.

Drag Increase After Engine Failure

Performance charts have been developed under the assumption that there is no change in the induced drag. The justification for this simplification has been given in the preceding section where it was shown that for purposes of obtaining climb and ceiling it is permissible to assume all increases in drag as being of the parasitic type. This assumption gives conservative results on calculated maximum velocity.

There remains, therefore, to determine the total increase in the equivalent parasite drag area when the multi-engine airplane is operated with one or more engines dead. This total parasite area increase will be made up of two components: First, the drag area arising from the negative thrust of the propeller on the engine not in operation; second, that arising from the increase in drag of the airplane. This latter portion includes the induced and additional parasite drags of the rudder, the additional drag of various other parts of the airplane such as fuselage, nacelles, ailerons, and the increase in the induced drag caused by the unsymmetrical flow of air over the wing.

An investigation of the available data on the negative thrust and torque characteristics of propellers has been made in the following. Approximate relations are developed for the friction torque of engines, since the drag of the propeller depends upon the resisting torque of the engine.

Flight test data on normal ceiling and ceiling with one engine out of operation have been analysed to determine the necessary increase in equivalent parasite area required to obtain the same results by calculations.

Data and relations which are given should be regarded as approximations of preliminary nature, since the complete data necessary for defining all of these relations are not available. Complete flight test data on absolute ceiling, rate of climb, and maximum velocity of airplanes operating after engine failure would be of great assistance in determining the necessary factors for this method.

Engine Friction Torque

The friction horsepower is a complex function of many factors, but the main variation appears to be with displacement and revolutions per minute. In addition, however, the friction horsepower is affected by gearing, altitude, throttle setting, blower and compression ratios, oil temperature, and mechanical design of the engine. In Figs. 3 and 4 the friction horsepower and ratio of torque to displacement are shown for various geared and direct drive engines having different blower and compression ratios. The

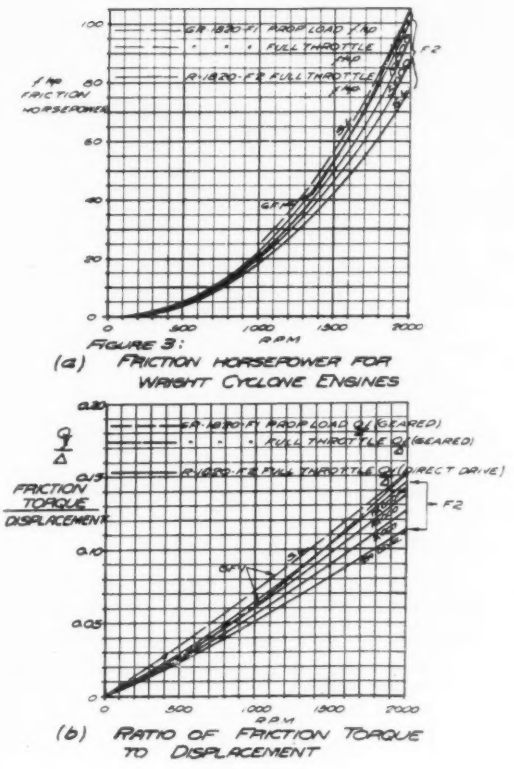


FIGURE 3:
(a) FRICTION HORSEPOWER FOR WRIGHT CYCLONE ENGINES

(b) RATIO OF FRICTION TORQUE TO DISPLACEMENT

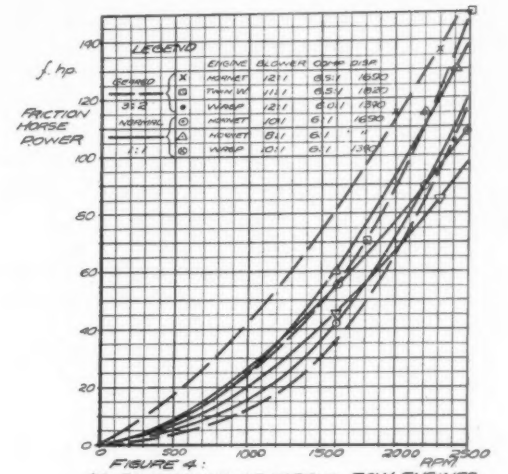
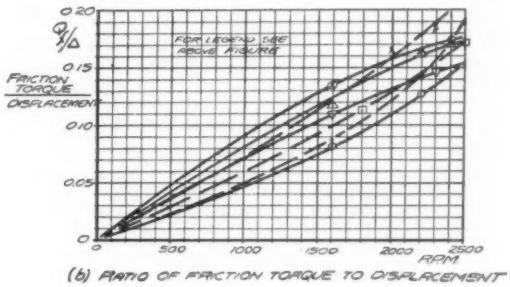


FIGURE 4:
(a) FRICTION H.P. OF VARIOUS P&W ENGINES



(b) RATIO OF FRICTION TORQUE TO DISPLACEMENT

effects of altitude and throttle setting are illustrated in Fig. 3. These engines have displacements of from 1,340 to 1,830 cubic inches, and normal maximum power ratings of approximately 500 to 800 brake horsepower.

Flight test results indicate that the engine r.p.m. after engine failure usually assumes a value of about 35 to 50 percent of the rated revolutions. When friction horsepower or torque curves are not available, an approximation to the torque can be obtained by the relation,

$$Q_f = k_1 \text{ r.p.m. } \Delta(1+k_2h)k_3/\text{G.R.}, \qquad (13)$$

where Q_f = friction torque at the propeller shaft (ft. lb.),
k_1 = constant,
Δ = engine displacement (cu. in.),
r.p.m. = engine revolutions per minute,
k_2 = constant,
h = altitude (ft.),
G.R. = gear ratio (≤ 1),
k_3 = constant (correction for geared engines).
(G.R. and $k_3 = 1$ for direct drive engines.)

Adjusting the constants according to Figs. 3 and 4, so as to give good agreement with r.p.m. in flight test, we get,

$$Q_f = 0.000057 \text{ r.p.m. } \Delta(1+0.00002h) \times [1.2/\text{G.R. (if geared)}], \qquad (14)$$

$$Q_f/\text{r.p.m.} = 0.000057\Delta(1+0.00002h) \times [1.2/\text{G.R. (if geared)}] \qquad (15)$$
$$= k_4, \text{ a constant for a given engine at any altitude.}$$

At 9,500 ft. with gear ratio of 0.687, and 1,820 cubic inch displacement,

$$Q_f/\text{r.p.m.} = 0.000057 \times 1{,}820(1+0.00002 \times 9{,}500) \times (1.2/0.687) = 0.216.$$

It is interesting to note that in normal full-throttle flight the torque is approximately constant; for negative thrust the friction torque is assumed proportional to the r.p.m.; and for the normal propeller load curve the torque varies as the square of the r.p.m. All of these relations are of the same general order of accuracy, often being sufficiently exact to be of much use.

It is recommended that engine test data be used for obtaining the torque when they are available; however, the expression for friction torque in Eq. (14) is believed to be sufficiently accurate for all normal calculations on performance after engine failure.

Propeller Drag

The drag or negative thrust of a given propeller depends principally upon the friction torque, velocity, blade-angle setting and propeller diameter. Wind tunnel tests on the negative thrust and torque characteristics of two-bladed propellers are reported in Reference 3, where the thrust and torque coefficients are plotted against the advance ratio reciprocal nD/V, for various combinations of wing and nacelle location.

The thrust and torque coefficients are defined by,

$$T_c = T/\rho V^2 D^2, \tag{16}$$

$$Q_c = Q/\rho V^2 D^3, \tag{17}$$

where T = thrust (lb.) (negative sign indicates force aft),
Q = torque (ft. lbs.) (negative sign indicates propeller turning engine),
ρ = density (slugs/cu. ft.),
n = revolutions per second,
D = diameter (ft.),
V = velocity (ft./sec.),
σ = relative density.

In Figs. 5 and 6 there is plotted the negative-thrust coefficient versus torque coefficient for a two-bladed propeller with a nacelle alone, and with wing and nacelle. Fig. 6 has been estimated for the propeller 30 percent of the wing chord ahead of the leading edge, from two tests with the propeller located approximately 10 and 50 percent ahead of the leading edge of the wing chord.

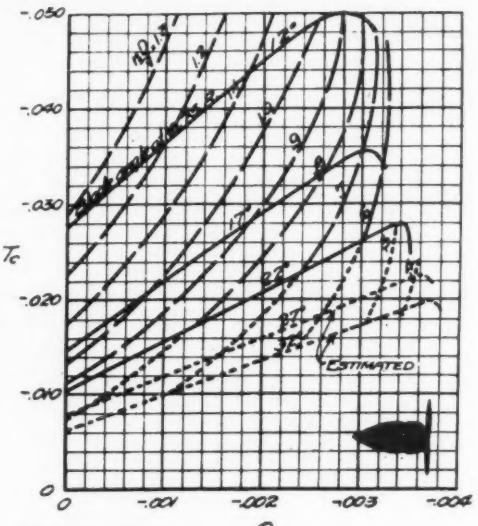


FIGURE 5:

NEGATIVE-THRUST AND TORQUE COEFFICIENTS OF A TWO-BLADED PROPELLER WITH NACELLE ALONE.

CURVES BASED ON DATA FROM NACA TECHNICAL REPORT 464.

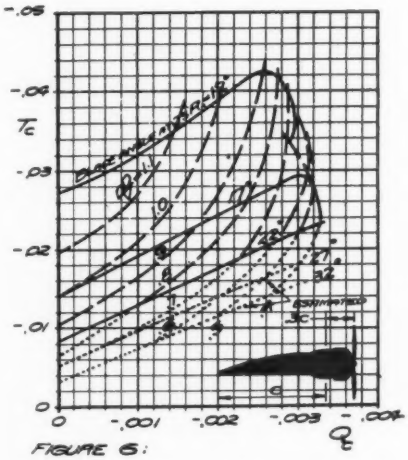


FIGURE 6:

NEGATIVE-THRUST AND TORQUE COEFFICIENTS OF A TWO-BLADED PROPELLER WITH NACELLE AND WING COMBINATION.

PROPELLER 30% OF CHORD FORWARD OF LEADING EDGE OF WING.

CURVES BASED ON DATA FROM NACA T.R. 903.

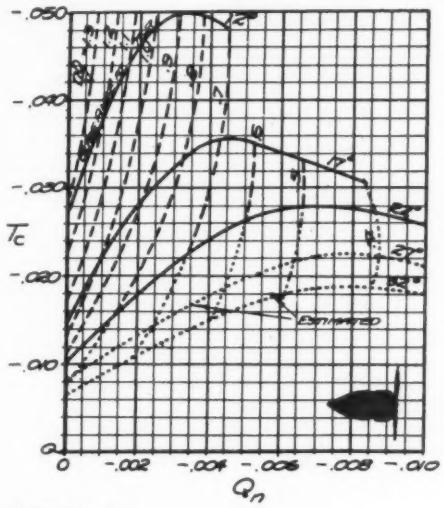


FIGURE 7:

NEGATIVE-THRUST AND TORQUE-R.P.M. COEFFICIENTS OF A TWO-BLADED PROPELLER WITH NACELLE ALONE

CURVES BASED ON DATA FROM NACA T.R 464.

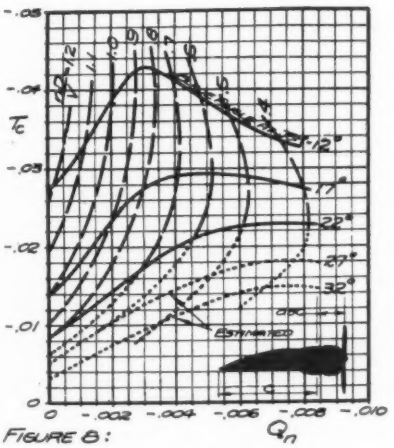


FIGURE 8:

NEGATIVE-THRUST AND TORQUE-R.P.M. COEFFICIENTS OF A TWO-BLADED PROPELLER WITH NACELLE AND WING COMBINATION - PROPELLER 30% OF CHORD FORWARD OF LEADING EDGE OF WING.

CURVES BASED ON DATA FROM NACA T.R. 464.

The equivalent parasite drag area of the propeller can be calculated from this curve by determining Q_c from Eq. (14) and obtaining T_c from Figs. 5 or 6. It is a function only of the thrust coefficient and can be obtained from

$$f_p = D_p/q = (B/2)(T/q) = (B/2)(T/\tfrac{1}{2}\rho V^2) = BD^2T_c \quad (T_c \text{ for two-bladed propeller in this equation}), \tag{18}$$

where B = number of blades,
q = dynamic pressure (lb./sq. ft.),
D_p = drag or negative thrust of propeller (lbs.).

For use in the curves, Q must be taken for two blades, since the tests were made on two-bladed propellers. For geared engines the negative torque must also be obtained for the propeller and not the engine crankshaft, hence

$$Q \text{ (for use in curves)} = (2/B) \times \{Q \text{ (engine crankshaft)/G.R.}\}. \tag{19}$$

Because the engine friction torque varies with r.p.m., it may be necessary to make several successive approximations in the use of Figs. 5 or 6 before obtaining the necessary compatible conditions of torque, velocity, and r.p.m.

It is convenient to define a new torque-r.p.m. coefficient, Q_n, because of the linear relation between friction torque and r.p.m. The necessity of successive approximations can be eliminated by plotting the negative-thrust coefficient versus this new torque-r.p.m. coefficient, which contains the ratio Q/n instead of Q. Q_n is defined as,

$$Q_n = (Q/\rho V^2D^3)(V/nD) = (Q/n)/\rho VD^4 = (17{,}200Q/\text{r.p.m.})/\sigma D^4 \times \text{m.p.h.} \tag{20}$$

The ratio Q/n will have only one value, hence Q_n need not be readjusted. T_c is plotted versus Q_n in Figs. 7 and 8.

The equivalent propeller drag area, $f_p = D_p/q$, can now be determined by the following alternate methods:

(1) Obtain Q_f/r.p.m. (or Q_f) from engine friction curves or Eq. (15) [or (14)].
(2) Estimate velocity, which for climb and ceiling is approximately 0 to 15 percent less than the normal speeds for these conditions.

(3) Calculate Q_n (or Q_c) by Eq. (20) [or (17)].
(4) Obtain T_c from Figs. 7 or 8 (5 or 6).
(5) Calculate f_p by Eq. (18).

In the event Q_c and Figs. 5 or 6 have been used, the engine revolutions, n, have to be determined from nD/V and checked with the original assumption. For Q_n, however, n determined from nD/V will be directly the correct value, provided Q/n is constant for the engine.

The drag of the propeller when locked in position, or free-wheeling, is of interest because of the possibility of decreasing or increasing the drag as desired by varying the blade-angle or negative torque. Furthermore, failure of the engine might be of such nature that the rotation of the propeller would be stopped.

The negative-thrust coefficients of the propeller when operating under various conditions have been plotted in Fig. 9.

The negative-thrust coefficient of a locked propeller decreases with increasing blade angle from -0.0250 at 0° blade-angle setting at 0.75 R. to a minimum of -0.0014 at approximately 87°. Above 13° blade-angle setting the free-wheeling propeller has less drag than the locked propeller, but below 13 degrees the negative-thrust coefficient rises rapidly to a maximum of about -0.107 at 2° blade-angle setting.

An interesting comparison of the magnitude of these negative thrusts for a modern transport airplane is given in the table below.

Still larger negative thrusts can be obtained by adjusting both torque and blade angle, but our interest in airplane operation after engine failure is chiefly in lowest negative thrust. The feathered propeller has only about 3 percent of the drag of the normal airplane, while the propeller operating against normal engine friction torque would have about 27 percent of the normal airplane drag. Adequate propeller control is of great importance in flight of multi-engine airplanes after engine failure, both for developing maximum positive thrust and reducing negative thrust to a minimum.

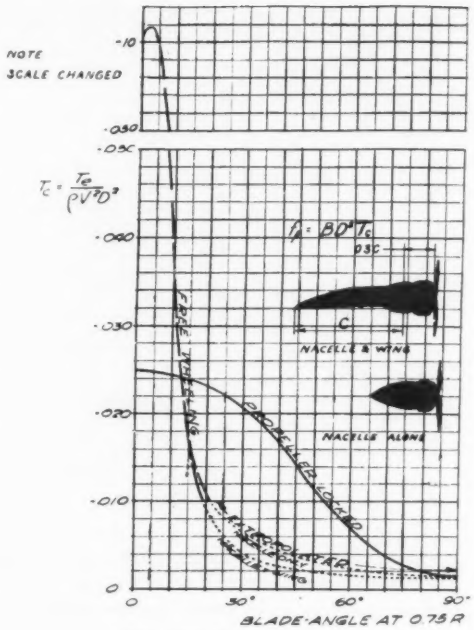


FIGURE 9:
VARIATION OF NEGATIVE-THRUST COEFFICIENT WITH BLADE-ANGLE SETTING FOR LOCKED AND FREE-WHEELING PROPELLERS.
CURVES BASED ON DATA FROM NACA TR 456

TABLE II.

Bimotor airplane with three-bladed 11 ft. propellers	Equivalent parasite area: 18.0 One propeller	18.0 Two propellers	% Airplane drag: 100 One propeller
Propeller 23°, turning against engine torque	4.9	9.8	27
" 23°, locked	8.2	16.4	46
" 23°, free-wheeling	2.6	5.2	14
" 88°, locked	0.5	1.0	3
" 88°, free-wheeling	0.5	1.0	3
" 2°, locked	9.1	18.2	51
" 2°, free-wheeling	38.9	77.8	216

Increase in Airplane Drag

The net difference between the total drag increase and the drag of the propeller represents the increase due to the rudder, fuselage, and additional induced drag, etc. The drag increment should be roughly proportional to the offset moment that must be balanced by the rudder. This moment arises from the eccentricity of the thrust and propeller drag.

Consider the airplane flying at approximately the attitude of zero yaw. An approximate analysis gives for the equilibrium between moments, as shown by Fig. 1,

$$f_v h = f_T d_T + f_p d_p. \tag{21}$$

Solving for f_v,

$$f_v = T_v/q = (T/q + f_p d_p/d_T) d_T/h. \tag{22}$$

Substituting the resisting equivalent parasite area for the equivalent thrust area, T/q,

$$f_v = (d_T/h)[f + f_i + f_{ex} + (1+d_p/d_T) f_p + \Delta f], \tag{23}$$

where d_T = distance of center of thrust from the plane of symmetry,
d_p = distance of center of propeller drag from the plane of symmetry,
h = distance from center of gravity to the center of pressure on the vertical surface,
f_i = equivalent induced drag area $= D_i/q$,
f_{ex} = equivalent area of excess thrust.

The equivalent area of excess thrust is defined as the excess thrust for climbing divided by the dynamic pressure,

$$f_{ex} = T_{ex}/q = 550 thp_{ex}/Vq = (Wdh/dt)/Vq$$
$$= 4.5\, CW/\sigma \text{ m.p.h.}^3 \text{ (in engineering units)}, \tag{24}$$

where T_{ex} = excess thrust (lb.),
thp_{ex} = excess thrust horsepower,
W = weight (lb.),
C = rate of climb (ft./min.),
dh/dt = rate of climb (ft./sec.).

f_{ex} can be obtained from Eq. (24) by estimating either the excess thrust horsepower or the rate of climb. A direct estimate of f_{ex} is usually sufficiently accurate.

Assuming that the ratio of increase in airplane drag, $\Delta f/f$, is proportional to the force on the vertical surface, we get,

$$\Delta f/f = \text{function}\,[(d_T/h)\{1 + f_i/f + f_{ex}/f + (1+d_p/d_T)(f_p/f)\}] = \text{function}\,[F], \text{ say} \tag{25}$$

which we shall approximate by a straight line,

$$\Delta f/f = A + KF \tag{26}$$

where A and K are constants depending upon the type and design of the airplane.

The relation in the brackets, F, has been chosen as the variable against which the increase of airplane drag is plotted. Forty percent of the span can generally be substituted for h, when the latter is not known.

The increase in airplane drag will differ for various conditions of flight as follows:

Case	Special condition (approx.)	F
Absolute ceiling	$f_i = f$, $f_{ex} = 0$	$(d_T/h)[2 + (1+d_p/d_T)(f_p/f)]$
Climb	$f_i = f$	$(d_T/h)[2 + (f_{ex}/f) + (1+d_p/d_T)(f_p/f)]$
Maximum velocity	$f_i = 0$, $f_{ex} = 0$	$(d_T/h)[1 + (1+d_p/d_T)(f_p/f)]$.

Calculations from flight test data on several multi-engine airplanes for the determination of the drag increase at absolute ceiling with one engine dead are given in Table III. The flight test data on normal ceiling and ceiling after engine failure have been reduced by the method here developed to determine the total parasite drag increase of the airplane. The results have been plotted in Fig. 10, which show the ratio of increase of airplane drag as a function of the factor F. The constant A varies from about 0 to 0.5, and K from about 0.4 to 1.3 respectively for airplanes of efficient and poor design for flight after engine failure.

TABLE III. *Analysis of flight test data on ceiling of multi-engine airplanes after engine failure*

Airplane	Engine not operating	Normal absolute ceiling	Ceiling with one eng. not operating	A	f	Propeller	D	Angle at 0.75 R.	V_{c_z} m.p.h.	b.hp.$_{cr}$ (each)	Displacement	Gear ratio	σ_{H_1}
Boeing YB-9	R L	24,400	6,800 "	7.3	23.4	3-bl.	11.5	27.7	112 (112)	600	1,860	0.667	0.816 "
Boeing Y1B-9	R L	21,000	3,500 2,200	10.35	27.3	3-bl.	9.83	21.5	101 98	600	1,570	0.714	0.902 0.937
Douglas Y1C-21	R L	16,100	None	16.2	26.7	2-bl.	9.0	16.2	—	350	975	1.00	—
Douglas XB-7	R L	20,600	2,800 "	10.8	23.4	2-bl.	8.44	20.2	107	600	1,570	1.00	0.921 "
Douglas XO-35	R L	23,300	5,500 7,650	8.2	24.9	3-bl.	9.83	21.5	110	600	1,570	0.714	0.848 0.795
Douglas XRD-1	R L	19,500	200 "	12.0	23.4	2-bl.	8.5	15.5	90	430	975	1.00	0.997
Boeing 247	R L	20,400	2,000	11.0	19.9	3-bl.	9.0	23.0	110	550	1,340	1.00	0.943
Douglas DC-2	R L	25,400	9,500	6.55	18.0	3-bl.	11.0	23.0 low pitch	113	710	1,820	0.687	0.750
Ford 5-AT	C R L	20,650	9,000 9,375 5,575	10.7	56.0	2-bl.	10.0 9.46 "	13.9 15.8 "	85 86 94	430	1,340	1.00	0.762 0.753 0.877

After some experience in the use of the method, the various items making up the drag increase ratio can be estimated closely enough to bring the calculated result within the experimental error of flight test.

It will be noted in Fig. 10 that the factor F is least when the thrust and the propeller drag axes are in the plane of symmetry, and increases as both the thrust and propeller drag offsets increase. It should be remembered that the apparently large percentage drag increase includes both the increase in parasite drag and any increase in induced drag, under the simplifying assumption which has been made.

Parasite Drag Ratio

The total drag increase ratio z needed for determining the performance is given by the sum of the various items as follows:

$$z=f_z/f=1+f_p/f+\Delta f/f. \qquad (27)$$

The additional airplane and propeller drag ratios are different for the various conditions of flight. Conservative values are recommended, especially in determining rate of climb, since the high slipstream velocity often seems to cause an increase in induced drag over that normally expected.

PERFORMANCE CHARTS

Charts have been developed from Eq. (12) for three cases of operation of multi-engine airplanes after engine failure, namely:

$x=0.50$.—This case represents airplanes flying on 50 percent of their total number of engines, such as a two-engine airplane flying on one engine, a four-engine airplane flying on two engines, etc.

$x=0.67$.—This case represents airplanes flying on 67 percent of their total number of engines, such as a three-engine airplane flying on two

TABLE III (*continued*).

Airplane	Eng. not operating	Q_f/r.p.m.$_p$	Q_a	T_c	f_p	f_p/f	z	$\Delta f/f$	$\Delta f/f$(Av.)	d_T/h	d_p/d_T	$F=\frac{(d_T/h)}{\{2+(1+d_p/d_T)(f_p/f)\}}$	nD/V	R.P.M. calc.	R.P.M. eng. flight test	V_c all engs.	V_{c_x}/V_c
Boeing YB-9	R	0.217	0.00233	0.0135	3.6	0.15	1.83	0.68	0.68	0.27	1.0	0.62	0.60	770	720	111	1.01
	L														700		
Boeing Y1B-9	R	0.161	0.00327	0.0237	4.6	0.17	1.50	0.33	0.46	0.27	1.0	0.63	0.76	960	950		
	L	0.157	0.00316	0.0246	4.0	0.15	1.73	0.58				0.62	0.77	950	850		
Douglas Y1C-21	R																
	L																
Douglas XB-7	R	0.095	0.00325	0.0215	3.1	0.13	1.56	0.43	0.43	0.26	1.0	0.59	0.74	830			
	L	"	"	"	3.1	"							"				
Douglas XO-35	R	0.167	0.00331	0.0245	4.7	0.19	1.76	0.57	0.40	0.26	1.0	0.62	0.75	1,030	800	115	0.96
	L	0.173	0.00366	0.0255	4.9	0.20	1.43	0.23				0.62	0.74	1,020	800		
Douglas XRD-1	R	0.056	0.00206	0.0290	4.2	0.18	1.72	0.54	0.54	0.17	1.0	0.40	0.95	890			
	L																
Boeing 247	R	0.079	0.00200	0.0173	2.8	0.14	1.66	0.52	0.52	0.25	1.0	0.57	0.74	800			
	L																
Douglas DC-2	R	0.216	0.00300	0.0204	4.9	0.27	1.55	0.28	0.28	0.27	1.0	0.69	0.71	930	1,000	130	0.87
	L																
Ford 5-AT	C	0.090	0.00239	0.0350	7.0	0.13	1.65	0.52	0.52	0.00	0.0	0.00	0.94	700	850		0.97
	R	0.091	0.00302	0.0310	5.5	0.10	1.58	0.48	0.95	0.14	2.0	0.32	0.83	660	800	88	0.98
	L	0.085	0.00222	0.0280	5.0	0.09	2.50	1.41		"	"	0.32	0.92	800	800		1.07

engines, a six-engine airplane flying on four engines, etc.

$x=0.75$.—This case represents airplanes flying on 75 percent of their total number of engines, such as a four-engine airplane flying on three engines, etc.

Parasite drag increases of 0, 50 and 100 percent have been used which correspond to $z=1.0$, 1.5 and 2.0 respectively. By interpolation between the various curves the performance of other types of airplanes, under various conditions, can be closely estimated.

Curves for the performance parameters and characteristics are given in Figs. 12 to 18.

Development

The method of development of the charts is as follows:

(1) For a given x, z and Λ, find the value of R_{v_x} which solves Eq. (12). Fig. 11 shows the method of solution.

(2) From R_{v_x} obtain T_{v_x} by Fig. 2.

(3) Obtain the parameters for flight after engine failure from Eq. (3).

(4) Obtain performance from the curves of Reference 1. This process may be repeated for various values of Λ, x and z to cover the cases desired. The included charts have been worked out to cover the usual range of values of Λ, and values of x and z as noted previously.

Use of Charts

In using these charts the general procedure will ordinarily be as follows:

(1) From the basic characteristics of the airplane the performance parameters l_p, l_s, l_t and Λ are obtained by Eq. (1), from which the usual performance characteristics on full power can be obtained as outlined in References 1 and 2. These must be properly modified for supercharged engines and controllable-pitch propellers. If performance has already been calculated or

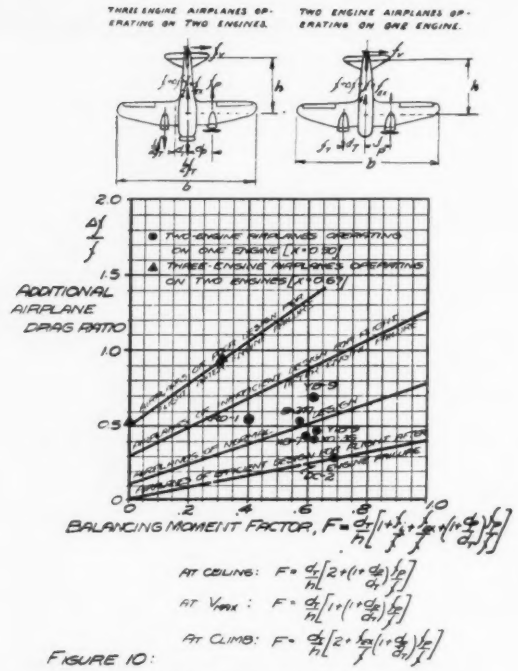

THREE ENGINE AIRPLANES OPERATING ON TWO ENGINES.
TWO ENGINE AIRPLANES OPERATING ON ONE ENGINE.
ADDITIONAL AIRPLANE DRAG RATIO
BALANCING MOMENT FACTOR, F =
AT CEILING:
AT V_{MAX} :
AT CLIMB:

FIGURE 10:
ADDITIONAL AIRPLANE DRAG AS A FUNCTION OF BALANCING MOMENT FACTOR

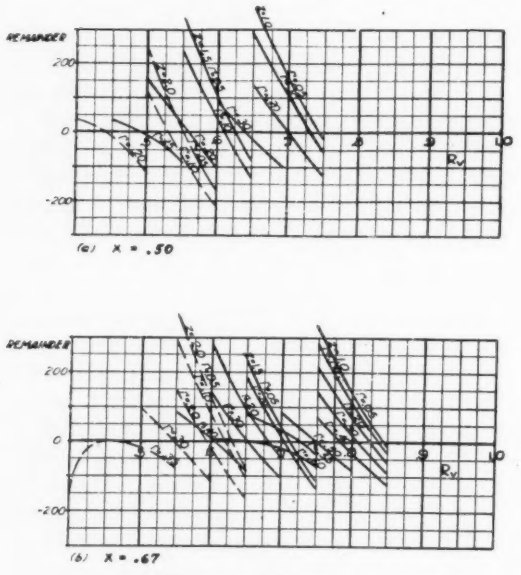


FIG. 11. CURVES FOR OBTAINING SOLUTION OF R_{V_2} FROM EQUATION (12)

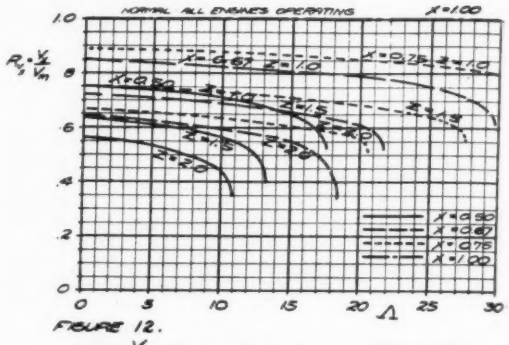


FIGURE 12.
$R_y = \frac{V_y}{V_m}$ AS A FUNCTION OF PARAMETER Λ AND PARASITE DRAG RATIO Z FOR MULTI-ENGINE AIRPLANES AFTER ENGINE FAILURE (SEA LEVEL).

X = RATIO OF NUMBER OF ENGINES OPERATING TO TOTAL NUMBER AVAILABLE

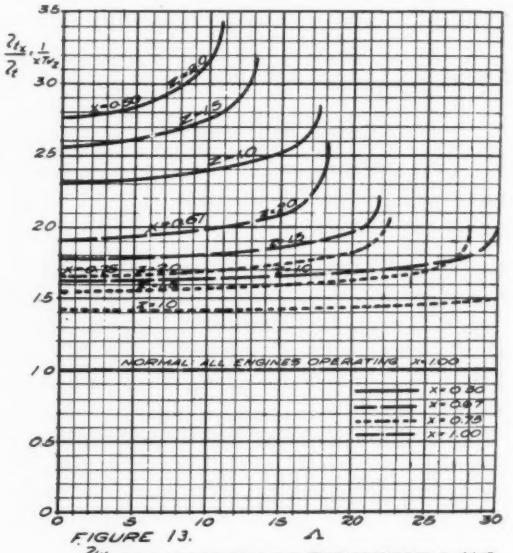


FIGURE 13.
$\frac{\gamma_x}{\gamma_t}$ AS A FUNCTION OF PARAMETER Λ AND PARASITE DRAG RATIO Z FOR MULTI-ENGINE AIRPLANES AFTER ENGINE FAILURE.

y = RATIO OF NUMBER OF ENGINES OPERATING TO TOTAL NUMBER AVAILABLE

determined from flight test, Λ and l_t can be obtained from the normal full-power curves in Figs. 17 and 18.

(2) The percentage drag increases resulting from the idling propeller and additional drag of the airplane are obtained from Figs. 5 to 10, hence z is determined. Different values of z

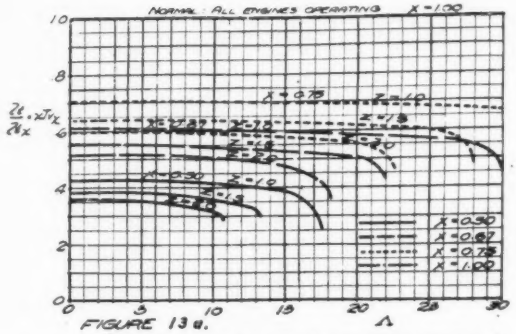


FIGURE 13a.

$\frac{l_t}{l_{t_x}} = x T_{t_x}$ AS A FUNCTION OF PARAMETER Λ AND PARASITE DRAG RATIO Z FOR MULTI-ENGINE AIRPLANES AFTER ENGINE FAILURE.

X = RATIO OF NUMBER OF ENGINES OPERATING TO TOTAL NUMBER AVAILABLE.

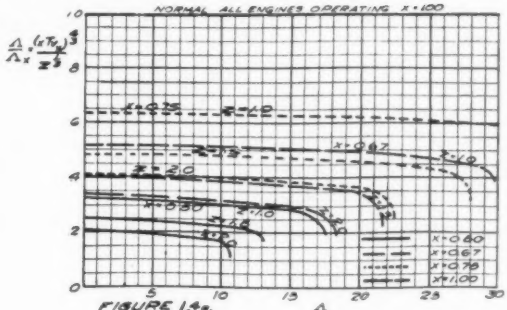


FIGURE 14a.

$\frac{\Lambda}{\Lambda_x} = \frac{(xT_{t_x})^{\frac{2}{3}}}{Z^{\frac{2}{3}}}$ AS A FUNCTION OF PARAMETER Λ AND PARASITE DRAG RATIO Z FOR MULTI-ENGINE AIRPLANES AFTER ENGINE FAILURE

X = RATIO OF NUMBER OF ENGINES OPERATING TO TOTAL NUMBER AVAILABLE

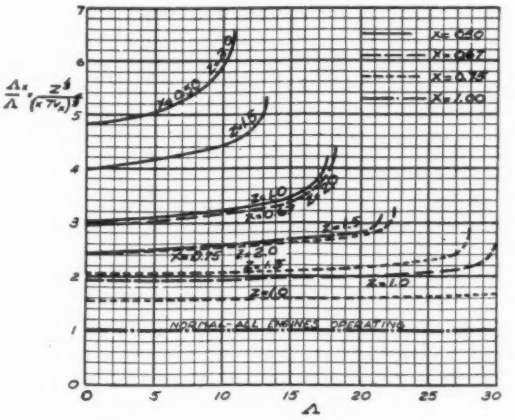


FIGURE 14.

$\frac{\Lambda_x}{\Lambda} = \frac{Z^{\frac{2}{3}}}{(xT_{t_x})^{\frac{2}{3}}}$ AS A FUNCTION OF PARAMETER Λ AND PARASITE DRAG Z FOR MULTI-ENGINE AIRPLANES AFTER ENGINE FAILURE

X = RATIO OF NUMBER OF ENGINES OPERATING TO TOTAL NUMBER AVAILABLE

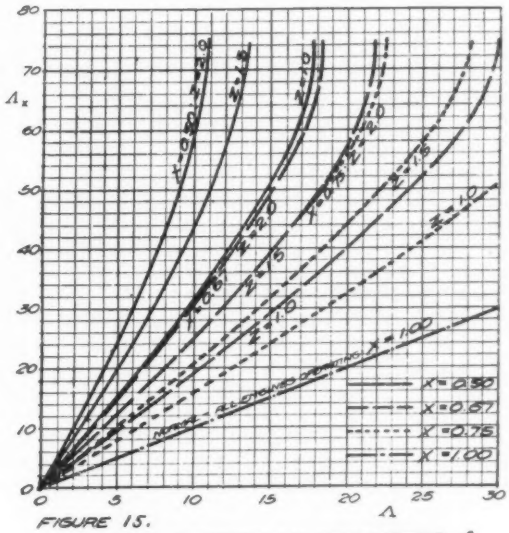


FIGURE 15.

Λ_x AS A FUNCTION OF PARAMETER Λ AND PARASITE DRAG RATIO Z FOR MULTI-ENGINE AIRPLANES AFTER ENGINE FAILURE

X = RATIO OF NUMBER OF ENGINES OPERATING TO TOTAL NUMBER AVAILABLE

should be used for determining the various characteristics.

(3) The principal performance characteristics are found from the normal values of the parameters l_p, l_a, l_t and Λ, and z by Figs. 16, 17 and 18. Alternately, the new values of the parameters can be calculated, or obtained through Figs. 13, 14 and 15, and z. Then the charts of Reference 1 are used to obtain the performance after engine failures.

Aerodynamic Design

Achieving reliability in multi-engine airplanes is largely dependent upon the proper aerodynamic design of the airplane. It is necessary that special attention be given to the design of the airplane for flight with one or more engines

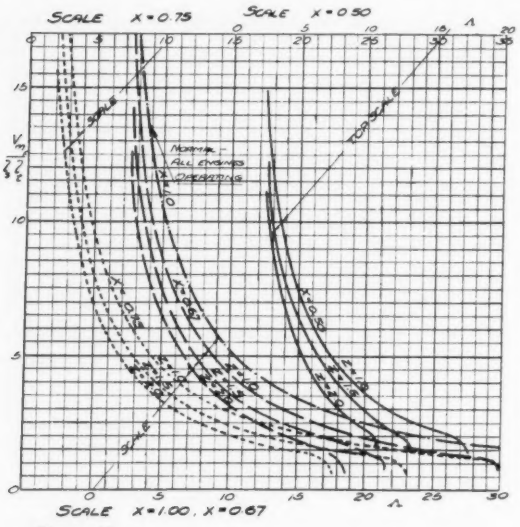


FIGURE 16

$\frac{V_{m_x}}{\sqrt[3]{\frac{Z}{C_f}}}$ AS A FUNCTION OF PARAMETER Λ AND PARASITE DRAG RATIO Z FOR MULTI-ENGINE AIRPLANES AFTER ENGINE FAILURE

V_{m_x} = MAXIMUM VELOCITY AT SEA LEVEL (M.P.H.)
X = RATIO OF NUMBER OF ENGINES OPERATING TO TOTAL NUMBER AVAILABLE

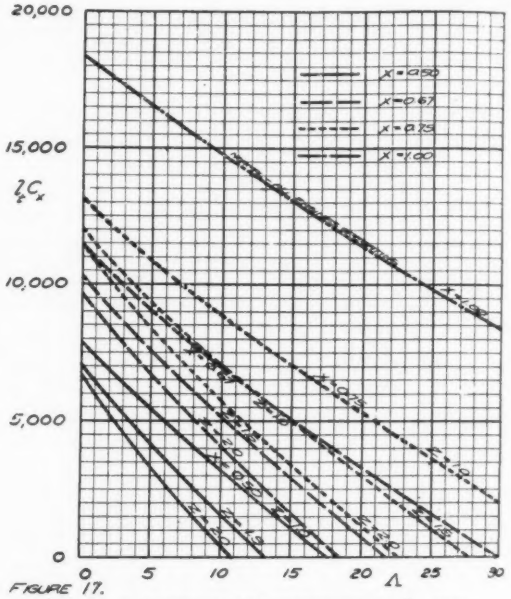


FIGURE 17.

$\sqrt[3]{C_f}\,C_x$ AS A FUNCTION OF PARAMETER Λ AND PARASITE DRAG RATIO Z FOR MULTI-ENGINE AIRPLANES AFTER ENGINE FAILURE

C_x = MAXIMUM RATE OF CLIMB AT SEA LEVEL (FT. MIN.)
X = RATIO OF NUMBER OF ENGINES OPERATING TO TOTAL NUMBER AVAILABLE

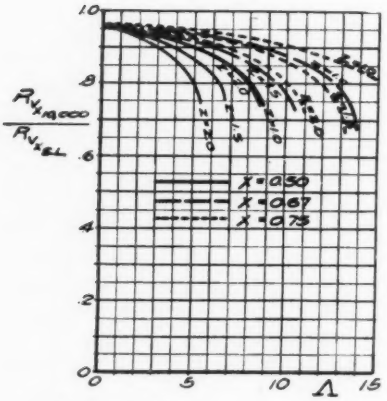


FIGURE 16a.

$\frac{R/C_{x\,10,000}}{R/C_{x\,S.L.}}$ AS A FUNCTION OF PARAMETER Λ AND PARASITE DRAG RATIO Z FOR MULTI-ENGINE AIRPLANES AFTER ENGINE FAILURE.

X = RATIO OF NUMBER OF ENGINES OPERATING TO TOTAL NUMBER AVAILABLE

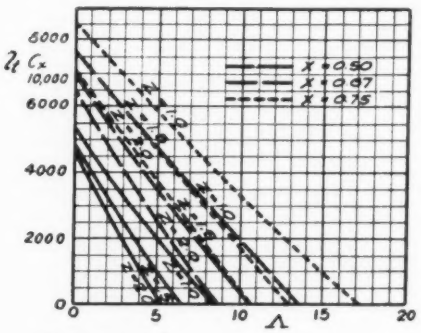


FIGURE 17a.

$\sqrt[3]{C_f}\,C_{x_{10,000}}$ AS A FUNCTION OF PARAMETER Λ AND PARASITE DRAG RATIO Z FOR MULTI-ENGINE AIRPLANES AFTER ENGINE FAILURE

X = RATIO OF NUMBER OF ENGINES OPERATING TO TOTAL NUMBER AVAILABLE

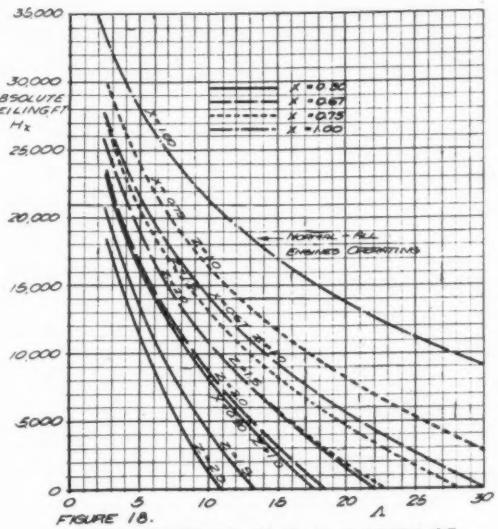


FIGURE 18.
ABSOLUTE CEILING H_x AS A FUNCTION OF PARAMETER Λ AND PARASITE DRAG RATIO Z FOR MULTI-ENGINE AIRPLANES AFTER ENGINE FAILURE
X = RATIO OF NUMBER OF ENGINES OPERATING TO TOTAL NUMBER AVAILABLE

out of operation. The multi-engine airplane should be definitely designed for this condition if the reliability consistent with the additional complication of many engines is to be realized. As has been previously pointed out, safety and reliability of the multi-engine airplane are not necessarily greater than that of a single-engine airplane, unless after engine failure it is capable of completing its mission in an efficient manner with adequate control.

Certain aerodynamic features are available which enable the engineer to design a multi-engine airplane that has good performance after engine failure. The principal considerations for obtaining most favorable operation are outlined below:

(1) The rudder should produce sufficient yawing moment at the zero yaw attitude of flight to counterbalance the moments resulting from offset thrust, idling propeller drag, and any adverse yaw due to aileron action. The magnitude of this moment should be ample to provide for the lowest velocity intended for operation, usually near the stall.

(2) The vertical surface should be designed as an efficient lifting surface based essentially on the criteria that would be used for judging a good wing design. It should be of high aspect ratio and so disposed that the efficiency of the surface is not impaired by adverse interference effects. The rudder angle necessary for producing equilibrium should not be too large because of the high parasite drag that might result.

(3) A rudder flap is needed of sufficient size to hold the rubber in the required position with zero control force. Likewise, the ailerons and elevators require trimming flaps sufficient to enable the airplane to be flown "hands off."

(4) Propellers should be of the feathering type in order to reduce their drag when an engine fails. When turning against the torque of the engine, the negative drag of a propeller in high pitch is slightly less than when in low pitch. For higher pitch settings a free-wheeling propeller has considerably more drag than the feathered type, but less than when it is turning against engine torque. Reducing the propeller drag decreases the rudder size required and the drag of the rudder.

(5) Span loading of the airplane should be as small as feasible (that is, large span and/or low weight) since span and weight have the greatest effect on ceiling of any of the airplane parameters. The problem of flight after engine failure is largely one of designing an airplane that has more than the usual capabilities in absolute ceiling.

(6) The general "cleanness" of design of the airplane and efficiency of all component parts must be kept at their highest possible value, since all favorable and unfavorable effects are magnified when operating after engine failure.

(7) The rudder moment required for balance should be investigated at the ceiling; especially for airplanes with highly supercharged engines, because aerodynamic force would there be reduced while thrust still remained large. In fact, bi-motored airplanes with highly supercharged engines will be found to require for single-engine operation a rudder somewhat out of proportion to that which would normally be satisfactory.

All of these factors should be given due consideration if it is desired to achieve the reliability and safety factor possible when flying with one or more engines out of operation.

Example of Use of Method

In order to illustrate the application of this method and the agreement between flight test results and calculations, the Douglas DC-2 Bi-motor Transport is used as an example since complete data on it are available.

Flight test results for full gross load reduced to standard performance conditions are as follows:

On Full Power

High speed at 8,000 ft.	213 m.p.h.
Crusing speed at 75 percent power at 14,000 ft.	200 m.p.h.
Maximum rate of climb at 8,000 ft.	1,000 ft./min.
Absolute ceiling	25,400 ft.

On Single Engine

	Full load	Less 1,000 lb. Fuel. (Half normal fuel load)
Absolute ceiling	9,500 ft.	10,800 ft.
Maximum rate of climb at 6,000 ft.	70 ft./min.	110 ft./min.

The performance on full power by reverse solution of the charts of Reference 1 yields the following performance parameters:

$$\Lambda_0 = 6.55 \text{ (see Fig. 18, normal operation)},$$
$$l_{t_0} = 10.4 \text{ (see Fig. 17, normal operation)},$$
$$f = 18.0.$$

Propeller Drag

For the 1,820 cubic inch engine, geared 16 : 11 at 9,500 ft.,

$$Q_f/\text{r.p.m.}_p = 0.000057 \times 1{,}820(1+0.00002 \times 9{,}500)1.2/(11/16) = 0.216 \text{ (Eq. 15)}.$$

With the three-bladed 11-foot propeller at 113 miles per hour set 23° at 0.75 R. in low pitch and 32° in high pitch,

$$Q_n = (17{,}200 \times 0.216)/(0.750 \times 113 \times 11.0^4) = 0.0300 \text{ (Eq. 20)}.$$

Then

$$T_c = -0.0136 \text{ (Fig. 8 for two-bladed propellers) for } 23° \text{ blade angle.}$$
$$= -0.0076 \quad " \quad " \quad " \quad " \quad 32° \quad "$$

and

$$f_p = 3 \times 11.0^2 \times 0.0136 = 4.9 \text{ for } 23° \text{ blade angle.}$$
$$= 3 \times 11.0^2 \times 0.0076 = 2.8 \text{ for } 32° \quad "$$

Likewise, the drag of the propellers locked and feathered are found from Fig. 9 to be:

	Locked		Free-wheeling		Feathered
Angle at 0.75 R.	23°	32°	23°	32°	87°
T_c	−0.00225	−0.0020	−0.0072	−0.0035	−0.0013
f_p	8.2	7.3	2.6	1.3	0.5

Additional Drag

For the offset thrust of 9.0 ft. and tail length of 33 ft.,

$$F = (9.0/33)\{2+(1+9.0/9.0)(4.9/18.0)\} = 0.69 \text{ at absolute ceiling},$$

and

$$\Delta f/f = 0.28 \text{ (for efficient design, Fig. 10)}.$$

Total Parasite Drag Increase Ratio

$$z = 1+(4.9/18)+0.28 = 1.55 \quad 23° \text{ at } 0.75 \text{ R.}$$
$$= 1+(2.8/18)+0.26 = 1.42 \quad 32° \text{ at } 0.75 \text{ R.}$$

Similarly for other cases of propeller settings,

	Locked		Free-wheeling		Feathered
Angle at 0.75 R.	23°	32°	23°	32°	87°
F	0.79	0.76	0.63	0.58	0.56
$\Delta f/f$	0.32	0.31	0.26	0.24	0.23
f_p/f	0.46	0.41	0.14	0.07	0.03
z	1.78	1.72	1.40	1.31	1.26

Absolute Ceiling

The absolute ceiling according to Fig. 18, for $\Lambda_0 = 6.55$ and $z = 1.55$ is

$H_1 =$ 9,500 ft. with inoperative propeller in low pitch.
$= 10{,}500$ ft. " " " high "

Approximately 1,000 ft. increase in ceiling is obtained by setting the idling propeller in high pitch. For the other propeller settings, the comparative single-engine ceilings are,

	Normal engine torque		Locked		Free-wheeling		Feathered
Angle at 0.75 R.	23°	32°	23°	32°	23°	32°	87°
Single-engine ceiling	9,500	10,500	8,400	8,700	10,500	11,100	11,500
Change in single-engine ceiling		+1,000	−1,100	−800	+1,000	+1,600	+2,000

By dumping 1,000 lbs. of fuel, which is about half the normal fuel load, Λ_0 is decreased to

$$\Lambda_{0\ (-1{,}000\ \text{lb.})} = 6.55 \times [17{,}000/18{,}000]^2 = 5.84$$

and the normal single-engine ceiling increases 1,400 ft. from 9,500 ft. to

$H_1 = 10{,}900$ ft. (less 1,000 lb. fuel with propeller at 23°).

Operation in Flight

Control of this airplane when operating on one engine was carefully studied with the result that it can be flown in this condition "hands off."

In one test a take-off was effected during which one engine was cut out after having traversed half of the take-off runway at 4,200 ft. above sea level. The airplane was climbed, flown at 8,300 ft. altitude, 1,000 ft. above the highest point of the transcontinental air line which is 7,300 ft. above sea level, and landed at the next regular airport, 5,100 ft. above sea level. The entire flight was made on the remaining engine without causing any unusual strain on the pilot or airplane. It is notable that on this entire single-engine flight an average terminal-to-terminal speed of approximately 124 miles per hour was made, which practically equals that formerly obtained with tri-motored equipment.

This illustration serves to demonstrate that a high degree of safety in operation of an airplane can be achieved by thorough study and application of the various principles and problems relating to flight after engine failure.

Conclusion

Reliability and safety in the operation of an air line are best served by multi-engine airplanes capable of completing under good control all required flights after engine failure.

In order that the airplane be capable of developing its full potentialities in flight after engine failure it is necessary that comfortable and sufficient rudder control be provided to maintain flight at approximately zero angle of yaw. The control must be sufficient to handle emergencies such as failure just after take-off, etc.

The performance of the airplane after engine failure can be calculated by a rapid parameter and chart method. The principal parameters required are the usual parasite, span and thrust horsepower loadings, l_p, l_s and l_t respectively, the parameter $\Lambda = l_s l_t^{4/3}/l_p^{\frac{1}{3}}$, and parasite drag ratio z. Charts for finding z and the performance after engine failure are included.

The influence of the various factors affecting the performance after engine failure is readily seen. It is important that span be increased to a maximum, and that weight and propeller drag

be reduced to a minimum. It is further desirable that the propeller offset from the airplane's plane of symmetry be as small as possible. The airplane should fly nearly at the attitude of zero yaw in order that drag remain low. The vertical surface should be of efficient aerodynamic design and have low drag with the rudder deflected.

For construction of the charts, all increase in drag of the airplane has been assumed to be of the parasitic type. This assumption has been found to be consistent with available flight test data. Should it be found desirable when sufficient data are available, all variations could be determined from the general relations, and charts developed therefrom.

Careful study of the various factors involved in flight after engine failure, particularly regarding control and performance, should enable the engineer to design an airplane that has control and performance satisfactory for any reasonable requirement. For multi-engine airplanes, the performance after engine failure should be regarded as a definite problem of design.

Outside of the purely mechanical reason that very large engines are not yet available, the principal justification for the multi-engine airplane is its possibility of continuing safe and satisfactory flight after partial engine failure. The importance of the problems of performance and control involved is, therefore, directly comparable to the basic problems of normal flight.

References

1. Oswald, W. Bailey: General Formulas and Charts for the Calculation of Airplane Performance. N. A. C. A. Technical Report No. 408, 1932.
2. Oswald, W. Bailey: Methods of Performance Calculation for Airplanes with Supercharged Engines. Prepared by R. B. Ashley. Air Corps Information Circular No. 679, 1933.
3. Hartman, Edwin P.: Negative Thrust and Torque Characteristics of an Adjustable-Pitch Metal Propeller. N. A. C. A. Technical Report No. 464, 1933.

Propeller Limitations on Aircraft Engine Design

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(Received May 1, 1935)

AIRCRAFT engine designers have long realized that propulsive efficiency is related to rotational speed, but the complete relationship between engine power, propeller speed, and airplane forward velocity has not, to the author's knowledge, been set forth. It is necessary that the aircraft engine designer understand this relationship in order to make intelligent selection of propeller shaft speed. This paper is an attempt to clarify the problem and to present, qualitatively, at least, the relationship between these variables.

When the values of airplane speed (m.p.h.) propeller rotational speed (r.p.m.) engine power (hp.) and atmospheric density (ρ) are determined, the maximum efficiency for a given propeller blade design is fixed. Stated more directly, the maximum efficiency which may be obtained by selection of a propeller with the most favorable pitch and diameter is a function of the speed-power coefficient,

$$C_s = \frac{.638 \text{ m.p.h.} \times \left[\frac{\rho}{\rho_0}\right]^{1/5}}{\text{hp.}^{1/5} \times \text{r.p.m.}^{2/5}}.$$

(For a consideration of this relationship, see Ref. 1, pp. 91–97.) It will be noted that the numerator of this quantity contains the air density and the airplane velocity, both of which may be regarded as airplane characteristics, since the air density is determined by the altitude at which the airplane is intended to fly. The denominator contains only characteristics of the engine. For any propeller family, it is possible to plot the maximum efficiency obtainable on a system of coordinates whose values are determined solely from airplane and engine characteristics. The coordinates of such a system are r.p.m.$^2 \times$hp., and m.p.h. $(\rho/\rho_0)^{1/5}$.

Fig. 1 is a plot of propulsive efficiency upon the coordinate system suggested above. It is essentially a rearrangement of the data given on page 263 of Ref. 1. In addition, the efficiency curves have been corrected for tip speed losses

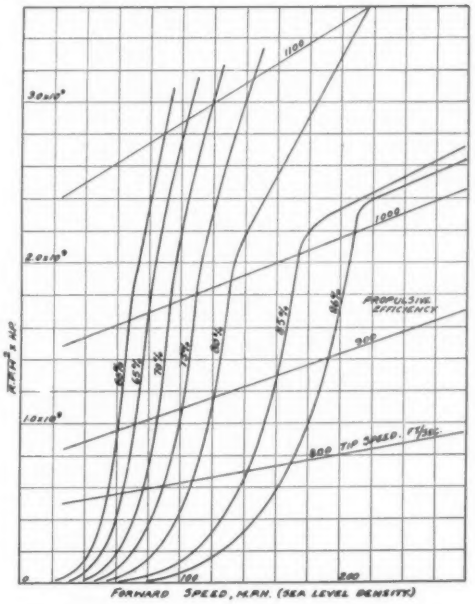

FIG. 1. PROPULSIVE EFFICIENCY AND TIP SPEED FOR MOST EFFICIENT PROPELLER.

by means of the chart on page 131 of Ref. 1. Below 1000 feet per second, the curves of constant efficiency in Fig. 1 are curves of constant C_s. Above 1000 feet per second the curves bend, due to the decrease in efficiency when the propeller tip speed approaches the velocity of sound. Efficiencies from 60% to 86% have been plotted. To the left of the 60% line the efficiency will be less than 60%, but the 86% line represents the limiting efficiency with the particular family of propellers chosen, and *the area to the right of the 86% line represents only 86% efficiency.* If a different family of propellers had been chosen, or if the body interference conditions had been different, the effect upon Fig. 1 would be to multiply the efficiencies by a constant factor whose value would be very near unity. The

[1] Weick, F. E., *Aircraft Propeller Design*, McGraw-Hill, 1930.

shape of the curves and the position of the curve of limiting efficiency would be affected only to a very small extent. Thus, the difference in efficiency between two points of the chart will be substantially correct for any family of propellers or any body interference conditions.

General Conclusions

Certain general conclusions can be reached by a consideration of the dimensions of the coordinate scales.

The propeller does not directly limit the r.p.m. of an engine, but it does limit the product r.p.m.$^2\times$hp. With geometrically similar engines running at the same piston speed, r.p.m.$^2\times$hp. is constant.[2] Under these conditions, and at the same airplane speed, propulsive efficiency is the same without regard to the absolute size of the engine. For a given efficiency, the value of r.p.m.$^2\times$hp. depends upon the forward speed and altitude at which the airplane operates.

Examples

The usefulness of the curves of Fig. 1 will be evident from the following examples. Suppose that we desire an engine with a cruising output of 300 hp. at 2000 r.p.m. for an airplane to cruise at 100 m.p.h. at sea level, and to operate a two-bladed propeller without the use of a reduction gear.

$$\text{r.p.m.}^2\times\text{hp.} = 2000^2\times 300 = 1.2\times 10^9.$$
$$\text{Forward Speed} = 100 \text{ m.p.h.}$$

The efficiency corresponding to these coordinates is about .74. By the use of a 2 to 1 propeller reduction, r.p.m.$^2\times$hp. is reduced to $.3\times 10^9$ and the corresponding efficiency is .82. The increase in efficiency can be evaluated in terms of performance, allowing for the necessary increase in weight of reduction gear and propeller.

As a second example, suppose we are interested in the design of an engine developing 1200 hp. at 15,000 feet for an airplane with a forward speed of 200 m.p.h. Suppose further that it is desired to limit the propeller tip speed to 900 feet per second in order to reduce propeller noise. What should the propeller r.p.m. be? To use Fig. 1 for altitudes above sea level, it is necessary to multiply the forward speed by the ratio $(\rho/\rho_0)^{1/5}$. For convenience, this factor is tabulated below.

Altitude (feet above sea level)	$(\rho/\rho_0)^{1/5}$
0	1.00
5000	.97
10000	.94
15000	.91
20000	.88
25000	.85
30000	.82

The sea level speed equivalent to 200 m.p.h. at 15,000 feet is

$$200\times .91 = 182 \text{ m.p.h.}$$

The intersection of the 182 m.p.h. line with the 900 feet per second tip speed line gives

$$\text{r.p.m.}^2\times\text{hp.} = 1.38\times 10^9$$

whence

$$\text{r.p.m.} = (1.38\times 10^9)/1200 = 1070,$$

and the propulsive efficiency is 85.7%. The propulsive efficiency under these conditions can be improved less than one per cent by reducing the propeller r.p.m. below 1070. In fact, inspection of Fig. 1 reveals that at speeds in excess of 180 m.p.h., propulsive efficiency is reduced from the maximum by more than one per cent only when the tip speed exceeds 1000 feet per second. With a fair degree of accuracy, Fig. 1 may be used for three-bladed propellers by multiplying the ordinate scale by 3/2. In the example above, the substitution of a three-bladed propeller gives

$$\text{r.p.m.}^2\times\text{hp.} = 3/2\times 1.38\times 10^9.$$

Such substitution does not materially reduce the propulsive efficiency unless it is already low due to operation at a low value of C_s. It usually simplifies the reduction gear problem. Substitution of a three-bladed propeller for a two-bladed one *without change in r.p.m.* may result in an improved efficiency.

Limitations of the Chart

A propeller is not always designed for maximum efficiency at any one flight condition, but

is a compromise which cannot be adequately represented upon the coordinates of Fig. 1. For this reason, the chart must be used with some discretion. The result of compromise is invariably a larger diameter propeller of smaller pitch than that which gives maximum efficiency at cruising speed. Since the efficiency of a propeller is a function of C_s, the curves of constant efficiency (constant C_s) will have the same shape for any compromise propeller, below the tip speed limitation. Due to the use of a larger propeller, the tip speed limitation will occur at a lower value of r.p.m.^{2}×hp. The maximum efficiency of the larger, lower pitch propeller will occur at a lower value of C_s which will result in each curve of constant efficiency being displaced somewhat to the left. The limiting efficiency will, of course, be somewhat lower. With the use of controllable pitch propellers, the accuracy of Fig. 1 is improved, since the design approaches more closely that for best efficiency at cruising speed.

When C_s is large, it is possible to increase the blade width, thereby increasing the power absorbed by the propeller, without materially decreasing the efficiency. If data were available to account for such permissible variations in blade design, an increase in slope of the curves of constant tip speed would result. This is not important except for very high speed (racing) aircraft.

Multiple Power Plants

An interesting conclusion may be drawn from a comparison of the propeller of a single motored airplane with those for a twin engine installation of equal power. The propellers for the twin engine installation may run at higher r.p.m. for the same efficiency, in fact, if each of the small engines operates at the same r.p.m.^{2}×hp. as the large engine, the efficiency (neglecting differences in body interference effects) will be the same. As is shown in Ref. 2, this condition will be satisfied if the engines are also geometrically similar. If r.p.m.^{2}×hp. is maintained constant, since the hp. for each propeller in the twin engine installation is one-half of the hp. for the single engine, it follows that the r.p.m. of each propeller of the twin installation is $\sqrt{2}$ times the r.p.m. of the single propeller. Likewise, the diameter of the single propeller must be divided by the $\sqrt{2}$ to obtain D for each of the smaller ones. Assuming geometric similarity, the propeller weight for the large engine will be $(\sqrt{2})^3$ times the weight of each propeller for the smaller engines. The propeller for the single engine will thus be about 40% heavier than two propellers for twin engines.

It may be shown that the stresses (including vibratory stresses) in geometrically similar propellers operating at the same forward speed on geometrically similar engines will be the same, and that the tip speeds will be the same (Ref. 2). Under these conditions, the propeller weight per hp. increases with increasing engine size.

In view of these facts, and the fact that weight per hp. of similar engines tends also to increase with size, it is perhaps worth considering whether the additional complication of multiple engine installations may not be justified by possible savings in power plant weight.

[2] Taylor, E. S., *Design Limitations of Aircraft Engines*, Aero Digest, p. 26, January, 1935.

Some Considerations Regarding Airfoils of Extremely Low Aspect Ratio

C. H. ZIMMERMAN, *National Advisory Committee for Aeronautics*

(Received September 19, 1934)

IN the early days of flying one of the designers' chief purposes was to so proportion his machine that it would lift a relatively large weight for a given amount of power. He used a low wing-loading and a high aspect ratio so as to derive lift from a large body of air and thus keep the drag due to lift at a minimum. With modern engines and controllable-pitch propellers, the problem of supporting a reasonable amount of useful load in the air at practical take-off speeds is no longer a serious one. Wing loadings have gone up steadily in the effort to achieve high load-velocity products for a given horsepower. Some considerations regarding airfoils with aspect ratios of the order of 1 to 1.5 make it appear that possibly still greater advances towards an economically as well as aerodynamically self-supporting aircraft may be made by eliminating the wings entirely and designing the fuselage to serve also as the lifting surface.

The most noticeable feature of the type of airfoils under consideration is the development of marked three-dimensional flow which continues without breakdown to very high angles of attack. This characteristic apparently exists regardless of plan form or airfoil section and was evident in the results of tests made with flat plates at an early date.[1] The effect is more pronounced for certain tip shapes, however, than for others.[2] The lift curves for a series of airfoils progressively varying in aspect ratio and with a possibly extremely effective tip are shown in Fig. 1. As will be seen from the figure, for aspect ratios of 1.51 to 0.75 the flow was decidedly more stable than for the conventional airfoil. No mathematical treatment of this phenomenon is available but there is an apparently logical explanation.

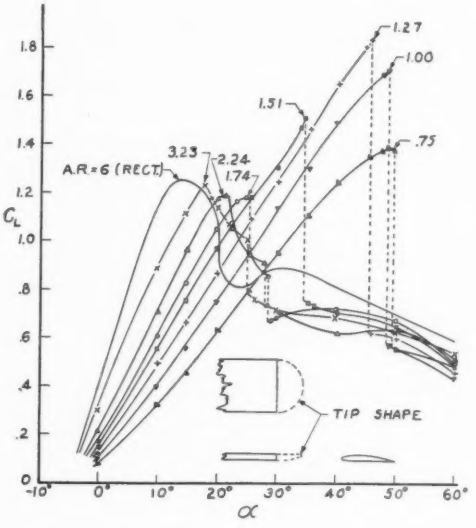

FIG. 1. Effect of Aspect Ratio on Lift Curve.

An airfoil producing lift dissipates energy into the air stream at a rate equal to the product of the induced drag and the velocity. This energy goes largely to establishment of vortex motion of the air with the vortex cores at the wing tips. As the aspect ratio of the wing is decreased, the vortex motion is increased and the well defined tip vortices are brought nearer together. For very low aspect ratios, the concentration of energy per unit of span becomes of such magnitude that the boundary layer tending to form over the rear portion of the upper surface of the wing is swept away and the flow continues without breakdown to very high angles of attack. The aspect ratio at which this phenomenon becomes apparent depends to some extent on the tip shape but did not differ greatly from 1.5 for three dissimilar tips reported in N.A.C.A. T. R. No. 431. The effect upon the maximum resultant force coefficient was quite marked and clearly defined the aspect ratio at which three-dimen-

[1] Eiffel, G., *The Resistance of the Air and Aviation*, Houghton, Mifflin and Co., 1913.

[2] Zimmerman, C. H., *Characteristics of Clark Y Airfoils of Small Aspect Ratios*. T. R. No. 431, N.A.C.A., 1932.

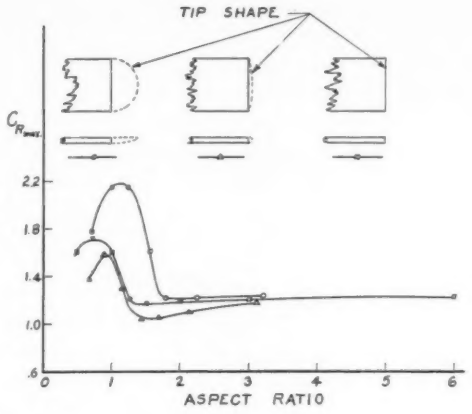

FIG. 2. Effect of Aspect Ratio on Maximum Resultant Force Coefficient.

sional flow became an important factor. (See Fig. 2.)

Another characteristic of particular interest is that rectangular airfoils with aspect ratios less than 2 gave lower values of induced angle of attack, and hence induced drag, than would have been indicated by accepted airfoil theory. This phenomenon was noted by Prandtl[3] and dismissed by him as not surprising because such an airfoil could not be expected to be approximated by a lifting line. It is surprising, however, that airfoils approximately rectangular in plan form but with the tips faired should give somewhat larger values of induced angle of attack than the theory indicates. The differences in profile drag and in angle of attack for infinite aspect ratio between airfoils with faired and with unfaired tips as determined in the usual manner were quite striking (see Fig. 3) and indicate a possibly fruitful field for research.

Efforts to use airfoils with extremely low aspect ratios have been few and the resulting designs have differed widely. Unfortunately, all of the machines of this type that have come to the writer's attention have fallen far short of the inherent possibilities of such craft because of errors in general design.

[3] Prandtl, L., *Application of Modern Hydrodynamics to Aeronautics.*, T. R. No. 116, N.A.C.A., 1925.

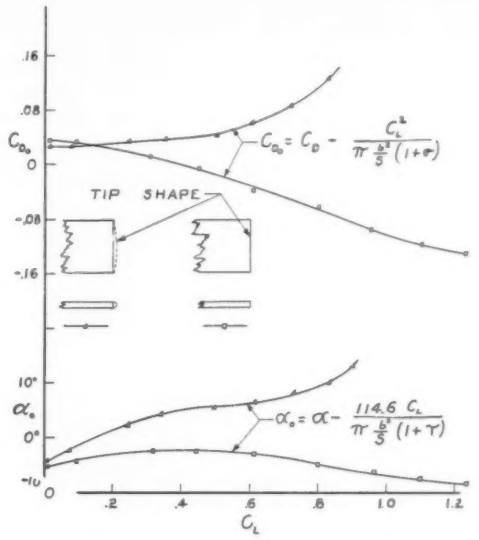

FIG. 3. Effect of Tip Shape on Profile Drag and Angle of Attack for Infinite Aspect Ratio.

In this paper it is not possible to discuss at length all the advantages and disadvantages of an all-fuselage aircraft. The following considerations however are worthy of mention.

Such a craft can be very efficient at high cruising speeds because the shape and dimensions permit enclosure of all items of load and equipment, except propellers and fin surfaces, within the lifting surfaces. For example, a craft with an aspect ratio of 1.25, a span of 16 feet, and a basic airfoil section such as the N.A.C.A. 0021 would be 40 inches thick at its maximum ordinate and over 30 inches thick at the maximum ordinate at each section through the central 10 feet.

The high ratio of depth to span, the small overall dimensions, and the load distribution which is possible all point to a high ratio of useful load to structural weight. It is easily possible to provide sufficient redundancy to insure against serious damage due to failure of a single structural item. The appearance of strength and solidity of such a craft will weigh heavily in the lay mind, a feature not to be regarded lightly by the designer.

The aerodynamic characteristics of low aspect ratio airfoils are such as to give good landing characteristics. As shown in Fig. 1, high maximum lift coefficients can be obtained by proper tip design. The angle of glide at slow speeds will be very steep, considerably steeper than can be obtained by the use of split flaps on an airfoil of conventional aspect ratio.

An all-fuselage aircraft should be amply powered. This is desirable for two reasons. A low aspect ratio craft can excel its conventional competitor only when operated at high cruising speeds where the induced drag is negligible. Also at take-off and when climbing a low power-loading is necessary for satisfactory performance.

The design of a satisfactory all-fuselage machine presents a number of puzzling problems, notably provision of adequate range of vision and a suitable landing gear. Some rather radical innovations in design will be necessary before these problems can be considered solved.

In conclusion special emphasis should perhaps be laid upon the fact that but a comparatively slight amount of research has been devoted to airfoils with low aspect ratios and it is possible that the interesting characteristics revealed by early tests may be capable of development to a much higher degree of usefulness. The low aspect ratio airfoils that have been tested have been derived from conventional airfoil profiles. Perhaps the evolution of a low aspect ratio airfoil by flattening a highly efficient streamlined body of revolution is worthy of consideration. From the practical point of view it is undoubtedly true that the type of design mentioned herein is far from being of proved excellence and that any such craft must necessarily be highly experimental in nature. On the other hand, it seems quite likely that the desire to obtain an extremely efficient craft for high speeds while retaining reasonable landing characteristics will lead an increasing number of designers to consider seriously the all-fuselage type.

ERRATA

Dr. Robert H. Goddard, who was credited in the May issue of the Journal with collaborating with Dr. Arnold M. Kuethe on the paper "The Scale of the Boundary Layer in the Atmosphere," should have appeared as the collaborator with Dr. Albert C. Erickson in the work which resulted in the paper on "Periodically Interrupted Flow Through Air Passages."

Dr. Goddard is Professor of Physics and Director of the Physical Laboratories at Clark University. He has been engaged for many years in research work on the rocket method of reaching extreme altitudes.

On Unstable Vortex Motion

HARRY T. CARTER, *University of California*

(Received December 7, 1934)

DUE to the very close relationship to turbulence, the study of the motion of vortices has been given much attention, particularly in regards to the stability of such motion.

One of the most outstanding works in this field was produced in 1911 by von Kármán[1, 2] in his study of the resistance to motion of bodies in a liquid.

According to von Kármán, there are two infinite rows of vortices extending behind the body and parallel to the direction of motion, one row originating from each side of the body. The sense of rotation is the same for all vortices in one row, but opposite to that of the other row. Assuming that the distances between adjacent vortices of one row are equal and the same for both rows, then there are two possible arrangements of the vortices. The first is known as the pairwise or symmetrical arrangement and is such that the vortices of each row are directly opposite the vortices of the other row. The second is known as the staggered arrangement and is such that the vortices of one row are opposite the midspan of the other row.

Von Karman showed mathematically that the pairwise arrangement is always unstable and the staggered arrangement is stable under certain conditions of spacing, the unstable arrangement tending to go into the stable arrangement. Photographs of the vortex arrangements always show the staggered arrangement with the spacing prescribed, within experimental limits of error. The present study was undertaken in an effort to show how the unstable case goes over toward the stable one. It was hoped to contribute some light upon the mechanism of turbulence.

Photographs were made of the vortex formation behind a half flat plate and the distribution of the vortices over the field of view was studied. The apparatus was a modification of that described by Ahlborn[3, 4] (see Fig. 1). The model is towed through the water by a car which also carries the camera for photographing the vortex motion. The pictures obtained are those of the flow of water past a fixed body and are described on this basis. The water was contained in a $1.5 \times 1.5 \times 12$ ft. channel. The lens of the camera was 3 ft. above the surface of the water. The model projected about one inch above the surface of the water. For smooth starting, the falling weight, W, was used. To obtain a uniform velocity, the car was held back by an oil brake, B, the speed being determined by the rate of flow of the oil through the by-pass. The brake worked properly only when the by-pass stopcock was fully open, so that predetermined speeds, and hence values of Reynolds' Number, were not possible. A small open top reservoir took care of the variable displacing volume of the plunger rod. Both weight and brake acted upon the car through the 5-ply pulleys, P, such that the car moved five times as far as the weight or brake.

The surface of the water was sprinkled with aluminum powder and illuminated by two 500 watt floodlights mounted on the car. The surface was cleaned and re-sprinkled before each run. The pictures were all taken with a still camera, the period of exposure of a motion picture camera

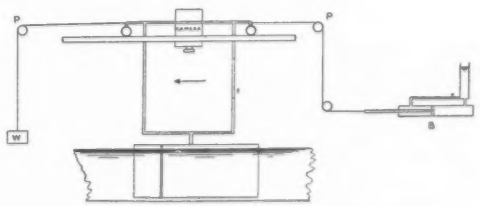

FIG. 1. Schematic Diagram of Apparatus.

[1] Th. von Kármán, "*Über den Mechanismus des Widerstandes den ein bewegter Körper in einer Flüssigkeit erfährt.*" Göttinger Nachrichten, math.-phys., Sept. 14, 1911.

[2] Th. von Kármán, "*Über den Mechanismus des Widerstandes den ein bewegter Körper in einer Flüssigkeit erfährt.*" Göttinger Nachrichten, math.-phys., Dec. 23, 1911.

[3] F. Ahlborn, "*Über den Mechanismus des Hydrodymanischen Widerstandes.*" Abh. a. d. Gebiet der Naturwisse, Bd. XVII. Hamburg 1902.

[4] O. Tietjens, "*Beobrachtung Strömungordnungen.*" Handbuch der Experimental Physik, Band 4 (1931), I Teil.

being too short to show the flow pattern on an individual exposure. Funds were not available to adapt a camera as described by Tietjens and Prandtl.[5] Exposures were made at any convenient place during the run.

The test plate (see Fig. 2) was a one-quarter inch brass plate, one inch wide and twelve inches long, bolted to a wall plate, also made of one-quarter inch brass plate. The outside edge of the test plate was chamfered to eliminate any effect of thickness. A thin sheet of galvanized iron was bolted to the bottom of the test and wall plates to prevent vertical flow of the water due to flow around the bottom of the test plate. A cloth scale was fastened to the top of the wall plate to serve as a reference for measuring vortex distances in the photograph.

By the method of images, the motion of the vortices is exactly that which would occur if the wall plate were removed and a second series of image vortices introduced opposite the actual

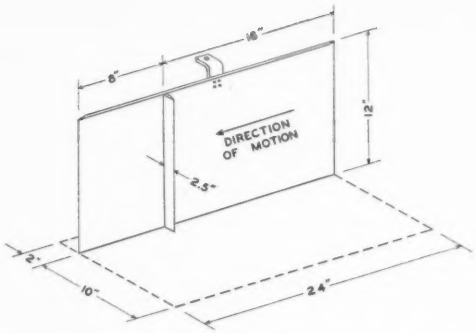

FIG. 2. The Test Plate with Wall Plate and Bottom Plate.

group. Accordingly, prints were made with reversed negative and joined to the direct print as shown in plate 1.

Vortex positions are plotted in Fig. 3. The curve was plotted by taking into consideration all the points obtained, although all points have not been indicated for reasons of clarity. The shape of the curve was determined by visual inspection of actual vortices observed during the experiment. The value of Reynolds' Number

[5] O. Tietjens and L. Prandtl, "*Kinematographische Strömungsbilder.*" Die Naturwissenschaften, 13 Jahrg., Heft 49/50. 1925.

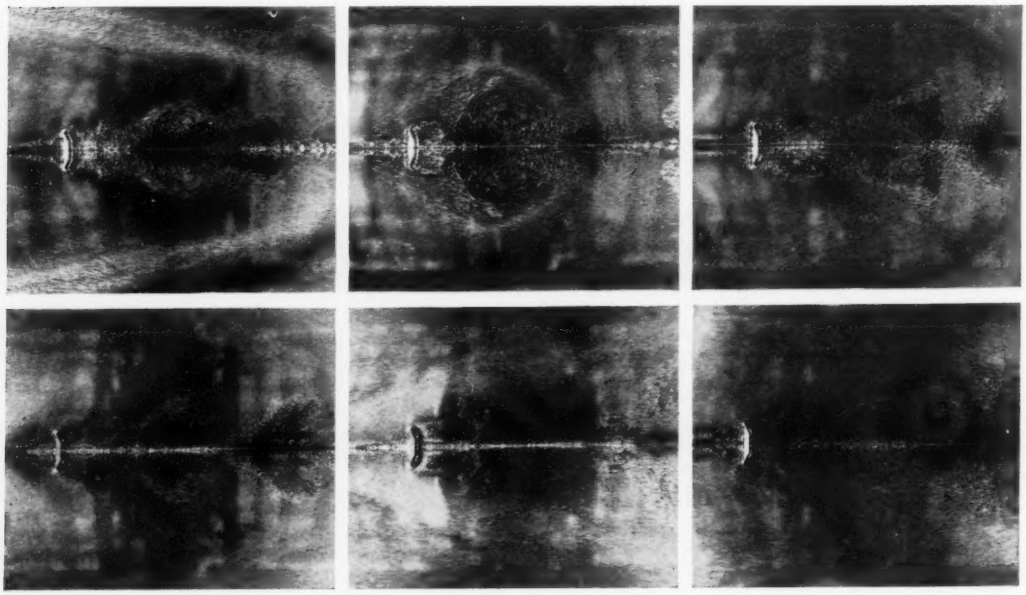

PLATE 1. Fictitious Full Plate. (Flow is from left to right.)

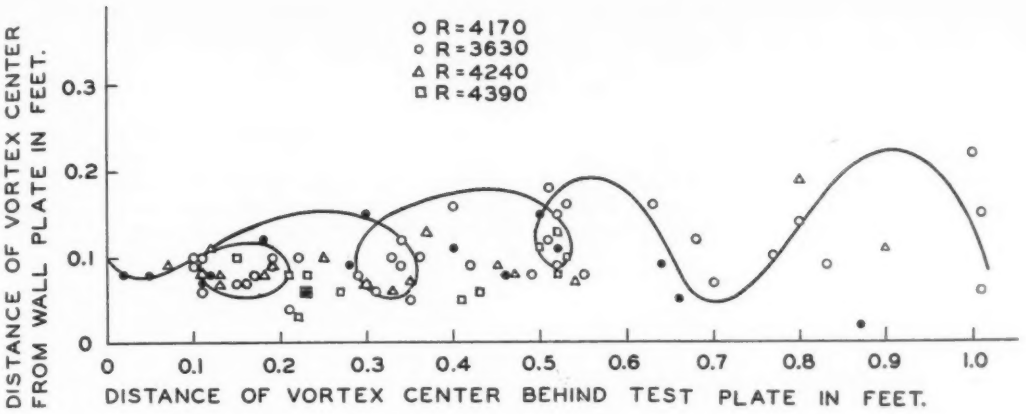

FIG. 3. The Vortex Path.

varied from 2740 to 6400, although the majority of the photographs were made at the Reynolds' Numbers indicated in Fig. 3.

The vortex motion is a combination of translation and rotation that is approximately a degenerate cycloid. If a coordinate system be assumed to move with the average speed and direction of a vortex, the vortex, relative to this system, moves in a spiral path. As the radius of the path increases, the linear velocity of the vortex perpendicular to the radius decreases, so that the path approaches a sinusoidal shape. With the cycloidal type of path, the vortex is searching, as it were, for the stable configuration, which is soon found in the conditions of the actual full plate, so that the unstable configuration as shown is never observed.

Due to viscosity, occasional large vortices caused secondary vortices about their edges. Also the location of the center of many vortices was complicated by indistinctness and shape. In addition to the above two causes, other factors, such as the motion of heavy machinery in adjacent buildings, etc., affected the results and helped cause the wide spread of the points in the figure.

Since the problem was two dimensional, it is not possible to apply the results directly to the problem of turbulence, which is quite distinctly a three dimensional problem. However, the shape of the curve gives a possible hint as to the part played by roughness in producing turbulence. The part played by viscosity is not portrayed here.

The Extraction of Energy from the Wind

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Equations are developed for the maximum available power from the wind for a wind power plant employing wings moving parallel to themselves along a closed path. It is shown that a single wing entering undisturbed air can extract two-thirds of the energy available in the wind. A conventional wing can extract several times more energy than a rotating cylinder. Comparing a plurality of conventional wings with a plurality of cylinders it is noted that more cylinders than wings are required to extract the same energy. The ratio is of the order of 5 to 1.

THE extraction of energy from the wind on a large scale has received considerable attention in Germany, Russia and the United States in recent years. Some of the proposed plants employ windmills formed of blades of conventional airfoil form while others use rotating cylinders.

The success of any wind prime-mover depends on the ability of the designer to spread a given amount of extractive structure over a very large area through which the wind blows because it is now known that localities can be found where the wind blows with a high degree of constancy; and the locality is near enough to make some industrial use of the power generated. It is therefore important to examine the area and determine how much energy may be extracted from the flow through it; for it must be realized that the extractive ability of a simple windmill is different from that of a turbine encased in a draft tube where the flow away from the turbine exit may have as low a velocity as desired.

A proposal[1] has been made to employ the windmill wheel itself, equipped with a rim, as a supporting structure so as to reduce the structural costs; also to mount a plurality of vanes on a track so that they travel a closed circuit with their spans vertical and parallel to each other. In a recent plan[2] the vanes are replaced by rotating cylinders.

It will be instructive first to investigate the amount of energy that one wing travelling a straight track can extract from the wind, assuming first that the wing always enters air never previously crossed by a wing or energy

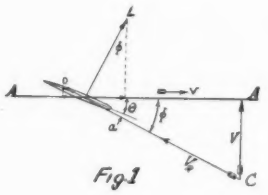


Fig. 1

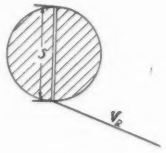


Fig. 2

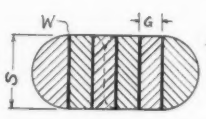


Fig. 3

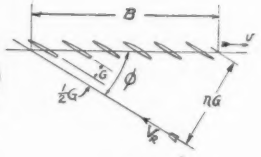


Fig. 4

extracting device. For the present purpose a wing will be regarded as any body creating a cross wind force. Let the lift of the wing be L and the drag be D; the wind velocity be V and track speed be v. The wind relative to the wing is the vector AC in Fig. 1. The vector, representing the lift, is normal to the relative wind while the drag vector lies along the relative wind. The resultant force along the track is

$$F = L \sin\theta - D \cos\theta$$

and the power P is

$$P = Fv = [C_L(\rho/2)A V_R^2 \sin\theta - C_D(\rho/2)A V_R^2 \cos\theta]v, \quad (1)$$

where ρ is the mass density. Then

$$P = (C_L \rho A V^3/2)[(1/\tan\theta \sin\theta) - (C_D/C_L)(1/\tan^2\theta \sin\theta)]. \quad (2)$$

If we differentiate P with respect to θ, holding C_L and C_D constant, and set the result equal to zero, we obtain the maximum power output of the wing. If we restrict θ to small angles it will

[1] G. A. Bennett, *U. S. Pat. No. 1,015,416*, 1912.
[2] J. D. Madarasz, *Wind Engine, U. S. Patent No. 1,791,731*, February, 1931.

be sufficiently accurate to put $\sin\theta$ equal to the tangent. For maximum power

$$\tan\theta=(3/2)(C_D/C_L) \tag{3}$$

and

$$P_{\max}=(2/27)[(C_L^3)/C^2_{D\max}]A\rho V^3. \tag{4}$$

This is the maximum power output for one wing of area A. There must be an upper limit for $P_{\max}$ which depends on the value of C_L^3/C_D^2, and the available energy in the wind.

It is known from aerodynamics that the drag coefficient C_D may be written in two parts.

$$C_D=C_{DP}+(C_L^2A/\pi S^2). \tag{5}$$

The first part is due to the friction of the wing surface, but the second part arises because of the finiteness of the span and the lift carried by the wing.

The value of C_L which makes C_L^3/C_D^2 a maximum is

$$C_L=(3\pi RC_{DP})^{\frac{1}{2}}; \qquad R=S^2/A=\text{aspect ratio} \tag{6}$$

whence

$$(C_L^3/C_D^2)_{\max}=[(3\pi R)^{\frac{3}{2}}/16(C_{DP})^{\frac{1}{2}}] \tag{7}$$

and

$$\tan\theta=6(C_{DP}/3\pi R)^{\frac{1}{2}}. \tag{8}$$

In a more general case

$$C_D=C_{DP}+jC_L^2+(C_L^2/\pi R)$$

so that for a maximum

$$C_L=(3\pi RC_{DP}/j\pi R+1)^{\frac{1}{2}}. \tag{9}$$

For many practical purposes Eq. (6) is satisfactory.

With the values of Eq. (7)

$$P_{\max}=(1/18)(3\pi R/C_{DP})^{\frac{1}{2}}(\pi S^2/4)\rho V^3. \tag{10}$$

The equation for $P_{\max}$ is put in this particular form because it has a physical significance. The power extracted may be referred to the mass of air passing through a circular tube whose cross section has the diameter S. Actually, the wing disturbs the air to great distances about itself but the disturbance at the wing tips represents a loss and its effect appears in the equation through the value of R. Later this phase may be examined more closely. For the present let us examine how efficiently the wing extracts energy from the wind.

In Fig. 2 the cross section of the tube is the shaded disk, and the air streaming through the disk is determined by the resultant velocity V_R; but the kinetic energy available to the wing from the wind per unit of mass is determined by the wind velocity V. Hence the kinetic energy T is

$$T=\frac{\rho}{2}\frac{\pi S^2}{4}V^2(V^2+v^2)^{\frac{1}{2}}, \tag{11}$$

$$T=\frac{\rho}{2}\frac{\pi S^2}{4}V^2\left[\left(\frac{V}{6}\sqrt{\frac{3\pi R}{C_{DP}}}\right)^2+V^2\right]^{\frac{1}{2}}. \tag{12}$$

The amount of energy which may be extracted was obtained in Eq. (4) and the ratio of the energy of Eq. (4) to that of Eq. (12) gives the efficiency

$$\eta=2/3(R/R+3.81C_{DP})^{\frac{1}{2}}. \tag{13}$$

If the air were frictionless the value of C_{DP} would be zero and then $\eta=\frac{2}{3}$. In other words, a wing always entering undisturbed air could ideally extract two-thirds of the energy of the wind in that air affected by the wing. The air so affected lies even at great distances from the wing but may be considered as the fluid flowing through the circle about the wing span as the diameter. The area of the circle will be called the sweep of the wing. When the disturbed air is treated as though it is only that flowing through the circle, the cross wind acceleration given to the air is assumed uniform throughout the circle. This fictitious mass of air is called the apparent mass.

If a plurality of wings are used the same method of analysis may be used. It is only necessary to find the sweep for the wing system. In Fig. 3 consider the five wings W. It is known from aerodynamic theory that this system has very closely the sweep indicated by the shaded area. The combination affects the flow very little at the outside surfaces of the wings, so that two half circles represent the sweep very closely. Between the wings the dotted lines define the actual sweep boundary, but for practical purposes it is accurate enough to take the whole rectangle. The sweep of the wing system of Fig. 3 may be equated to the sweep of a fictitious monoplane of span k_nS. Then if n is the number of wings

$$(\pi S^2/4)+(n-1)GS=(\pi(k_nS)^2/4)$$
$$k_n=[1+(4(n-1)/\pi)(G/S)]^{\frac{1}{2}}. \quad (14)$$

The coefficient k_n is the well known equivalent monoplane factor. If the wing system has a great lateral extent in comparison with the height of the wings the half circles may be neglected or assumed equal to the rectangle between two wings. The end wings are never very efficient in a closed system. Then

$$k_n=(4nG/\pi S)^{\frac{1}{2}}. \quad (15)$$

The equivalent aspect ratio of the wing system is then $k_n^2S^2/nA$.

Replacing the single wing values in equation (4) by the multi-wing values

$$P_{\max}=[(3\pi^3)^{\frac{1}{2}}/72][(k_nS)^3/(C_{DP}nA)^{\frac{1}{2}}]\rho V^3. \quad (16)$$

Consider a power plant of breadth B for which the power is to be expressed in terms of B and S. From the geometry of Fig. 4 it is noted that

$$nG=B\sin\theta. \quad (17)$$

so from Eq. (15)

$$k_n^2=(4/\pi)(B/S)\sin\theta. \quad (18)$$

From Eqs. (18) and (16), since

$$\sin\theta=\tan\theta=(6/k_n)(C_{DP}nA/3\pi S^2)^{\frac{1}{2}}$$
$$k_n^3=(24B/\pi S)(C_{DP}nA/3\pi S^2)^{\frac{1}{2}}. \quad (19)$$

If this value for k_n^2 is substituted in Eq. (16), then

$$P_{\max}=2/3BS(\rho V^3/2). \quad (20)$$

Also, from Eqs. (18) and (19) it follows as a close approximation that

$$\tan\theta=[3C_{DP}(nA/BS)]^{\frac{1}{4}} \quad (21)$$

for the production of maximum power. Using this as the pitch angle for an airscrew blade at 0.7 radius and an angle of attack corresponding to C_L^3/C_D^2 an approximation to the best windmill blade setting is obtained.

Thus, a power plant comprising a plurality of wings moving as a unit into undisturbed wind can extract $\frac{2}{3}$ of the energy in the air passing through the sweep of the plant or wing system. A sailing ship may therefore obtain as an ideal limit $\frac{2}{3}$ of the energy in its sweep for the propulsion of the craft. In a real plant of the stationary type, the wings retraverse the same path and it therefore appears that the coefficient of the power equation should be reduced and the path speed for maximum power should likewise be changed. A value of the coefficient may be established as follows.

It may be shown readily by the same reasoning as used in propeller theory[3] that one-half the retardation velocity occurs ahead of and one-half behind the plane of the extractive device.

The energy removed at a plane of area BS will determine the magnitude of the retardation velocity w_2. The power extracted is then

$$P=\tfrac{1}{2}BS(V-w_1)[V^2-(V-w_2)^2] \quad (22)$$
$$=2\rho BS(V-w_1)^2w_1 \quad (23)$$

where w_1 is the retardation velocity at the plane and w_2 is the final retardation velocity. $w_1=w_2/2$. If P is differentiated with respect to w_1 and set equal to zero, it is found that $w_1=\frac{1}{3}V$ for a maximum value of P. In that case

$$P_{\max}=16/27BS(\rho/2)V^3. \quad (24)$$

The value of 16/27 which represents the maximum efficiency of the power device has proved disappointing to proponents of wind power devices and in some cases has led to a denial of its validity. It is claimed that the power device will affect the air at great distances from the power device and that these effects are not included in the development of equation (24). These objections may be dismissed completely if BS is the "sweep" of the power device.

It is true that the development leading to the value of 16/27 does not explicitly state the marginal conditions at the edges of the plane BS but the specification of uniform retardation across the plane area implies a prevention of "spillage" at the edges.

The air is affected at great distances, and all these effects are represented in the area of uniform velocity change—that is, the sweep or cross section of the fictitious tube of flow.

The value of 16/27 will not be attained in practice with a simple windmill because the wind cannot be retarded uniformly over the disk area and there will be frictional losses. A housing

[3] H. Glauert, *The Elements of Aerofoil and Airscrew Theory*, p. 201, University Press, Cambridge, London, 1926.

or a hub fairing may of course act as a draft tube and materially improve the efficiency.

Replacing the coefficient of $\frac{2}{3}$ by that of 16/27 we obtain the following equations for the maximum power available from a "stationary" power plant.

$$k_n^3 = (64B/3\pi S)(C_{DP}nA/3\pi S^2)^{\frac{1}{2}}, \quad (25)$$

$$\tan\theta = 6(C_{DP}nA/3\pi k_n^2 S^2)^{\frac{1}{2}} = 6(C_{DP}/3\pi R_a)^{\frac{1}{2}}, \quad (26)$$

$$P_{\max} = (16nS^3/81)(3/C_{DP}A)^{\frac{1}{2}}(G/S)^{\frac{3}{2}}(\rho V^3/2) \quad (27)$$

or

$$P_{\max} = 16/27BS(\rho V^3/2). \quad (28)$$

It is interesting to return to Eqs. (3) and (4) and to note that there is an analogy with the airplane. It is well known that for a given horsepower available the best rate of climb of an airplane occurs when C_L^3/C_D^2 is a maximum. Then the weight of the airplane times the rate of climb may be regarded as power derived from the relative wind and is analogous to $P_{\max}$ of Eq. (4). Hence without any further analysis an aeronautical engineer is able to answer a question concerning the best airfoil form to obtain the maximum power output of a wind power plant utilizing a single wing and not subject to appreciable interference effects.

To provide a continuous generation of power the path about which conventional wings move must be closed and the attitude of the wings must be changed continuously to obtain the maximum power output. Every 180° the wings must point to a different side of the path. As a first approximation the sweep may be taken as the projection of the wing system on a plane normal to the wind direction, doubled if the leeward wings are sufficiently downwind. In a rotor plant of a given path velocity the rate of rotation corresponds to the change in angle of attack and every 180° the direction of rotation must be reversed.

There are several bases upon which conventional wing and rotor power plants may be compared. From the commercial point of view, the basis is, of course, one of the final cost of the energy extracted. The best results for both are not obtained where the same number of wings and rotors are used because it is practicable to run the wings at a higher speed than the rotors and so to use less of them. Hence it will be instructive to compare the plants on the basis of the same power output, which will include the effect of the relative track speeds because the gap is determined. For this purpose Eq. (26) may be used and solved for n.

$$P_{\max} = (16nS^3/81)(3/C_{DP}A)^{\frac{1}{2}}(G/S)^{\frac{3}{2}}(\rho V^3/2) \quad (29)$$

and

$$n = (81S^3/8\rho V^3)(C_{DP}A/3)^{\frac{1}{2}}(S/G)^{\frac{3}{2}}. \quad (30)$$

To make a comparison with a conventional wing plant it is necessary to evaluate the profile drag coefficient for a rotating cylinder. Lift and drag data are available from a few tests but accurate data on the power required to rotate the cylinder is lacking. An estimate should also be made of losses due to stopping and reversing the direction of rotation of the cylinder which is necessary at the ends of the diameter of the circuit. The mass of the cylinder is so large that an appreciable loss of energy may result. In addition the reversal of rotation will churn the air within the cylinder and cause a loss of energy residing in the air of such disorganized motion that it is difficult to see how any of this energy could be recovered. This is not true of the cylinder itself for one can imagine readily that the deceleration of the cylinder can be utilized to accelerate another cylinder at the opposite side of the track. At least in a wind power plant used for the generation of electricity this should be readily accomplished. Finally, there is the friction of the bearings and the losses in the auxiliary motor and transmission.

The analysis here presented, which is intended only as a first approach to the problem, is restricted to an estimation of the energy to translate the cylinder and to rotate it against external air friction. In view of the final results of this analysis it appears to give a good qualitative comparison and with proper care a good quantitative result also.

The power consumed in rotating the cylinder against the external resistance is obtained from the following considerations. The velocity of the air varies from point to point along the surface of the cylinder. There is then a variable slip between the cylinder and the surrounding air. The magnitude of the slip at any point may be

found from the value of the velocity for a frictionless fluid as given by theory and the known peripheral speed on the surface of the rotating cylinder. According to theory the value of C_L is given by

$$C_L=(2\int V_s ds/2aU)=(\Gamma/aU), \qquad (31)$$

where ds is the differential arc at radius a, V_s is the velocity along the surface, and U is the undisturbed wind velocity a great distance ahead of the cylinder. Also, according to theory $\Gamma=\int V_s ds$ is a constant for any line encircling the cylinder. In the case of a circular cylinder

$$\Gamma=4\pi^2a^2n, \qquad (32)$$

n=revolutions per unit of time.

The theoretical velocity at any point on the cylinder is

$$-V_s=2U\sin\theta+(\Gamma/2\pi a), \qquad (33)$$

where θ is the angular coordinate. The difference in the velocities at any point on the cylinder is

$$V_D=2U\sin\theta+(\Gamma/2\pi a)-2\pi rn \qquad (34)$$

$$=U(2\sin\theta+(C_L/2\pi)-\gamma) \qquad (35)$$

where

$$2\pi an=\gamma U \qquad (\text{when } a=r). \qquad (36)$$

In other words V_D is the velocity of the air relative to the rotating cylinder. If C_{Df} is the coefficient of friction the torque required to rotate the cylinder is

$$Q=\int_0^{2\pi} C_{Df}\frac{\rho}{2}SU^2\left(2\sin\theta+\frac{C_L}{2\pi}-\gamma\right)^2 ad\theta. \qquad (37)$$

A value of $C_{Df}=0.00365$ was determined upon using Eq. (38) on page 70 of *Engineering Aerodynamics*, by W. Diehl.

Since the square of $\sin\theta$ will mask the alternations in the sign, the torque must be obtained by integrating between points on the cylinder cross section where the relative velocity is zero. These points are given by

$$\theta=\sin^{-1}[(\gamma-C_L/2\pi)/2]. \qquad (38)$$

The computations of the torque and power required for a rotating cylinder have been made and the results presented in Fig. 5. The power has also been divided by $\rho AU^3/2$ to furnish a non-dimensional coefficient. It is interesting to note that at a lift coefficient of 6 the horsepower required to rotate a cylinder (diameter 22 ft. and height 100 ft.) in a resultant wind of 40 m.p.h. is 178, a not insignificant amount, and one which will entail a rather expensive equipment.

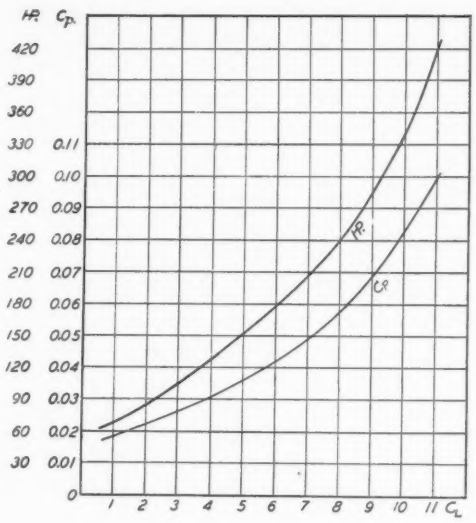


FIG. 5.

The reversal of the cylinders requires time and precludes the use of a high track speed. A low track speed requires a large number of rotors and hence a high initial cost.

The non-dimensional coefficient C_P has the same significance as C_{DP} and may be added directly to it to obtain an equivalent total profile drag coefficient. However, the profile drag of a rotating cylinder does not vary with the lift in the same manner as the profile drag of a wing. At zero lift, for instance, the flow past the cylinder is decidedly turbulent but upon rotation of the cylinder a portion of the turbulent wake will disappear and the lift will increase. Also, the induced drag should be calculated by a more refined method than usual since at large lift coefficients there is an appreciable deflection downward of the tip vortices themselves.

In the development given earlier C_{DP} was assumed constant and since this analysis is only a first order approximation the profile drag coefficient has been taken as constant at 0.21. If the analysis is confined to a small range near

the most efficient lift coefficient the departures from constancy in C_{DP} will not be large.

Upon this basis it will be observed from Eq. (29) that for the same number of units and G/S ratio the powers are inversely to the $(0.25)^{\frac{1}{3}}$ and $(0.01)^{\frac{1}{3}}$, respectively, for wings and rotors. If, however, a larger number of rotors than wings are used the power output of both systems can be the same on the basis of the assumptions made regarding C_{DP}.

It has been assumed for one thing that C_{DP} was constant but the same qualitative conclusions are obtainable if C_{DP} varies as C_L^2. It has also been assumed that always

$$C_L = (3\pi R C_{DP})^{\frac{1}{3}}. \tag{39}$$

This will not remain true at large lift coefficients especially near the maximum lift.

For conventional wings an assumption that C_{DP} varies as C_L^2 is sufficiently valid for moderately thick wings, but more experimental data is necessary for rotating cylinders to assure that the rate of increase is of the same order. The coefficient needed is one including values from both the internal and external flow and the bearing friction.

It appears from Eq. (30) that for the same power output and the same gap-span ratio, the number of rotors is proportional to the $(C_{DP})^{\frac{1}{3}}$. Since C_{DP} for the rotor is of the order of 0.25 including C_P and for the wing 0.01 it appears that the greatest disadvantage of the rotor power plant is its demand for such a large number of units which are costly and probably expensive to maintain.

A more detailed analysis involving step by step calculations with experimental data would show somewhat different numerical results but would not alter the general conclusions. In the design of a plant such detail computations should, of course, be made.

Conclusions

A wing system advancing into virgin air should extract ideally two-thirds of the energy passing through its sweep.

A single rotor can develop about one-fifth the power of a conventional wing if there is no limit placed on the track speed of either.

The rotor plant is excluded from the use of high track speeds because of its high profile drag. Even if high track speeds could be efficiently obtained aerodynamically, difficulty would be experienced in starting and stopping the massive cylinders rapidly enough and with economical machinery, since the higher the track speed the higher the rate of rotation required for efficient operation.

The cost of a wing unit will be appreciably less than the rotor unit.

The rotor plant will require more units than a wing plant as determined by the ratio of the square roots of the profile drag coefficients or about five times as many.

Engine Development—A Forward Look

Abstract of Lecture delivered April 5, 1935, before the Washington, D. C. members of the I. Ae. S., at the Cosmos Club

D. R. PYE, *Deputy Director of Scientific Research, Air Ministry, England*

MR. PYE observed that it was necessary to look behind as well as forward, because, in his view, successful engine development was usually based on what had gone before, and progressed by a series of small steps, each one consolidated before the next could be taken. The greatest idea was no more than a will-o'-the-wisp until it has been worked out in practical detail, because an engine lived or died by its perfection in detail. During the last five years the weight per horsepower of aircraft engines might be said to have been halved, from $2\frac{1}{2}$ to $1\frac{1}{4}$ pounds per horsepower. This had been achieved by:

(1) Improvements in the fuel.
(2) Improvements in combustion chamber design, in piston design, in bearing design, in valve material and design, in air-flow control and fin design.

Each of these might be regarded as an improvement of detail, but the total result was phenomenal.

In England there had been one radical departure in the development of the sleeve-valve to replace the poppet valve. This was of some special interest since it derived from a scientific examination some eight years ago as to what were at that time the limiting factors in engine output. These were considered to be:

(1) Speed, in which the spring-controlled poppet valve was a serious difficulty.
(2) Detonation, which was accelerated by the presence of a hot exhaust valve.

Research by Ricardo had shown that a sleeve-valve cylinder was capable of giving high volumetric efficiency and that there appeared to be no mechanical limit to engine speed when a sleeve valve was employed. Furthermore, for the same fuel and speed the compression ratio could be raised about one ratio.

The practical development of the sleeve-valve was confronted by some formidable difficulties, but the end to be gained appeared to justify the necessary effort. The next step in the development was made by the Bristol Company which had proved that it was possible to run a steel sleeve in an aluminium air-cooled cylinder, and they had further successfully tackled the problems of developing manufacturing methods, maintaining appropriate clearances, controlling oil consumption, providing satisfactory working surfaces on the sleeves, and overcoming the difficulties of cold starting.

A single experimental engine was built in the form of a nine-cylinder, air-cooled radial, which had successfully passed all ground tests, as well as many hours of severe flying tests. The results of these trials had been sufficiently satisfactory to encourage the building of several more engines for development.

Having dealt with this line of contemporary development, Mr. Pye remarked that the limiting factors in engine power output appeared still to be the difficulty of the fuel and speed, and, in addition, the provision of lubricating oils which would be chemically stable at high temperatures and provide good lubricating properties. He remarked that, if the surfacing of materials could be developed so that it was possible to operate a piston in a much hotter cylinder than at present, that would immediately make it possible to develop more power per cubic inch of swept volume.

On the question of future engine size Mr. Pye remarked that, whereas it might be that land machines had now reached their economic size for air transport, there seemed to be good arguments for building considerably larger flying boats, such as increased comfort and seaworthiness. The largest of the present American boats employed four 800-h.p. engines. If the designers would accept six engines on the wing, and normal development provided a thousand horsepower each, that would allow of nearly 100 per cent increase of total weight. Should engine designers, perhaps, be so bold as to try to develop much larger power units, up to 2,000 horsepower? And, if so, how? There are very serious

difficulties in the way of increasing cylinder size, and the general consensus of opinion appeared to be that increase of engine power must be obtained by increasing the number of cylinders rather than their size. Was it arguable that for the sake of their low rate of fuel consumption very large engines should be of the Diesel type? Experience in England with the four-cycle Diesel engine was that it could be built as a perfectly satisfactory engine for flying, but that it seemed improbable that it would be able to compete with the petrol engine on the basis of weight per horsepower under take-off conditions, considering the rapid progress which the petrol engine was making both in regard to weight per horsepower and fuel economy.

The two-stroke cycle offered a substantial increase in the horsepower obtainable per unit of swept volume from a Diesel, but hitherto the only practical form of two-stroke Diesel engine, namely, the Junkers, was of an essentially heavy type from the fact that it employed two six-throw crankshafts. Attempts had been made in England, and were continuing, to develop a two-stroke Diesel engine of the single-piston type working in a sleeve-valve cylinder. It had not been found possible to maintain so satisfactory a fuel economy in the two-cycle as in the four-cycle form. This was probably due to the fact that, in order to get an adequate scavenge of the cylinder, it was necessary to cut down the expansion stroke by an early opening of the exhaust valve. The short time available for the breathing operations of the two-stroke engine made it doubtful whether it would be able to compete with the four-stroke petrol engine to which there seemed very little effective speed limit. Another point which must be remembered in connection with the two-stroke engines was that, in order to get an adequate scavenge even at about 1,700 r.p.m., it was necessary to have a high pressure of the scavenge air and a scavenge blower large enough to provide a volume of air about 130 per cent of the swept volume. As regards the possibility of the two-stroke petrol engine, Mr. Pye remarked that ultimately the limit of horsepower per cylinder when using the four-stroke cycle appeared to be the difficulty of getting rid of the waste heat and that, unless the two-stroke cycle was easier to cool, it appeared probable that the limit of horsepower per cylinder would be reached at about the same power output, although at a lower crankshaft speed. It must, however, be remembered that, as he had already observed, the two-stroke cycle was likely to be less efficient and therefore that there would be more waste heat to be got rid of for the same power available at the crankshaft.

In regard to the possibilities of employing steam power in the air, Mr. Pye observed that, although he had received reports of plants showing a weight per horsepower as low as about $3\frac{1}{2}$ pounds and that weight might very possibly be reduced, a more serious drawback to his mind seemed to be that, whereas with the internal combustion engine the waste heat to be dissipated in the radiator of a 500 b.hp. engine would be about 250 hp., in the case of a steam turbine of similar output it would be necessary for the condenser to dissipate at least 1,000 hp. The cost of this, expressed as an increase of drag of the aeroplane, seemed likely to be quite prohibitive.

QUESTIONS ASKED MR. D. R. PYE FOLLOWING HIS LECTURE, AND HIS REPLIES

J. H. Geisse

What are the material and process for treating the surface of the sleeve-valve?

A chrome nickel steel with a high coefficient of expansion has been chiefly used, in conjunction with nitrogen hardening of the surfaces.

In the sleeve-valve 2-stroke-cycle engine are the heads recessed and with this arrangement does gumming occur?

In the type of sleeve-valve developed in England the heads are recessed. Gumming of the lubricating oil around the sealing rings in the head is undoubtedly one of the chief troubles to be encountered, but it has been found possible to get over this by careful design and adequate cooling of the head.

Major James H. Doolittle

What are the relative weights of the sleeve-valve and poppet-valve engines of the same power?

The weights of two radial air-cooled engines of the same cylinder size and general design would be substantially the same. The power for the sleeve-valve might be expected to be rather higher with the same fuel and there should be

greater scope for increasing the power of the sleeve-valve by steady development.

Isn't it true that the aircraft sleeve-valve engine will be more difficult to lubricate satisfactorily than the poppet-valve engine?

The single sleeve-valve, with its combined reciprocating and rotating motion is very satisfactory from the point of view of its lubrication. The two problems associated with it are those of cold starting and control of oil flow to prevent excessive consumption. As to the first, we have no experience yet below 32°F., but the second can be solved by satisfactory design.

Does Mr. Pye have available any information on the comparative temperatures of aluminium pistons in sleeve-valve and poppet-valve aircraft engines?

The measurements of piston temperatures under real working conditions is an exceedingly difficult problem. While no accurate figures are available for high speed working, it is probable that with the sleeve-valve the piston is 20–30°C. hotter than with the poppet-valve under comparable conditions.

G. T. Hemmeter

Is there any work being done on the development of the internal combustion turbine?

About 8 years ago we considered the feasibility of the internal combustion turbine. At that date the conclusion was reached that further work was not worth while until materials were available with higher strength properties at high temperatures. Since then, there has been a considerable advance in this respect and perhaps the time has arrived to review the question again.

Edward P. Warner

To what extent was the experience gained in the development of fuels for the Schneider Cup Races used in directing future research in the development of fuels for military and commercial aircraft engines?

The fuel used was so entirely special to the circumstances that I doubt if the experience gained has had any application in practice. The special fuel consisted of a large proportion of methyl alcohol, benzol, a little water and certain blending agents. The rate of consumption in pounds per b.hp. hour would be impossibly high for regular use owing to the low calorific value of methyl alcohol.

What progress is being made toward the international standardization of fuels for aircraft engines?

Standardization of the fuels themselves is scarcely to be looked for so long as some people are ready to pay more for their fuels than others, but we in England are working in co-operation with The Aircraft Gasoline Detonation Sub-Committee of the S.A.E. on the standardization of methods of fuel rating, and we look forward, in the near future, to the possibility of agreement upon a common test engine and methods of test on both sides of the Atlantic.

Aircraft Engine Lubrication

Paper read before members of the I. Ae. S. at Columbia University, New York City, April 15, 1935

E. L. BASS, *Director of Aeronautical Research of the "International Shell Group"*

ANY discussion on this subject may be expected to introduce that of the purely physical and chemical properties of oils, and perhaps to attempt to define that elusive quality known as "oiliness." This will certainly not be attempted on this occasion, as apart from being quite outside the scope of the author, aircraft engine manufacturers and operators are concerned only with practical results and it is with these that we are chiefly concerned in the development of the most suitable lubricating oils.

For some time past it has been evident that appreciably different results have been obtained in Europe to those in the United States and whilst conditions of operation and the types of aircraft used may have some influence on this, the different types of oils used have played an important part. One of the most striking differences appears to be in the overhaul periods obtained, 500 to 700 hours being the regular running times between overhauls obtained on many of the chief airlines operating in Europe and the Far East. Prior to the use of the specially compounded oils on which these results are obtained, oils similar to those in common use in the United States had permitted only 300 to 400 hours to be run between overhauls under exactly similar conditions.

These results have all been obtained on comparatively low output engines, but this does not necessarily detract from the interest of the subject before us; namely, the lubrication of high output engines of the future.

As the specific output of engines is increased, conditions for lubrication will become more arduous and unless the requirements for an oil of higher lubricating value ("oiliness") and resistance to deterioration under high temperature conditions are met, excessive wear and even bearing failures may occur due to the greater loading of the frictional surfaces.

It is well known from laboratory experiments that the addition of dopes (fatty acids, etc.) and fatty oils results in considerable improvement in lubricating value. One of the best known oils possessing this characteristic is castor oil, although it has other serious disadvantages which completely preclude its use for economical commercial airline service. It is still used in Europe mostly on stunt engines which are producing powers of the order of those envisaged by the introduction of new fuels of very high octane number. This is chiefly on account of the ability of castor oil to provide the required additional degree of lubrication needed by heavily loaded bearings, etc.

The original work carried out by Messrs. Ricardo & Co. for the Shell Company shows that, whereas a straight mineral oil could not be found to provide satisfactory lubrication for a then representative air-cooled aero engine, a suitably compounded oil was capable of doing so. At the same time, an oil was found which gave freedom from sludging and other disadvantages usually associated with mineral oils to enable very considerable improvements in overhaul periods to be obtained. As previously mentioned, 500 to 700 hours (on engines of both American, British, French and German manufacture) is a normal period between overhaul periods in European airline service, and even so, the limiting factor is not then one of depreciation of the oil, but rather the mechanical necessity for the servicing or renewal of some part of the engine. With further mechanical development there is every reason to believe that overhaul periods of 1000 hours will be obtained in the near future.

Success obtained in this connection has led to many interesting investigations and particularly methods of testing, since it has not yet been possible to develop laboratory tests from which the performance of lubricating oils can be accurately predicted. The fact that most of the important lubricating oil specifications for aircraft engine oils completely exclude compounded oils is of interest and is justified on the grounds that it is not possible yet to specify any simple laboratory test or series of tests for compounded oils which will exclude those, of which there are many, which are likely to be unsuitable for

blending with mineral oils for aircraft engine lubrication.

It may be said that one of the most important characteristics of lubricating oils is the way in which they are capable of holding sludge and the products of oxidation in suspension. This might, in fact, be termed their solvent properties. Some of the most stable oils available, that is, according to laboratory tests, are well known to cause severe carbon formation and sludging when used in an engine for any length of time. Nevertheless, the oil drained from such engines will be found to retain its original properties remarkably well, again—according to laboratory tests.

During the use of such an oil, however, it will have thrown out those undesirable deposits in the crankcase and on to the pistons of the engine which involve more frequent overhaul for cleaning and correction of lubrication oil consumption which increases abnormally through the oil control rings becoming choked with sludge, etc. By suitable selection and treatment of the fatty components for aircraft oils the necessary solvent properties may be obtained which result in the maximum cleanliness of the engine and normal oil consumption being maintained over long periods of operation. Incidentally, this function of certain compounded oils has been found to be of considerable advantage in compression ignition aircraft engines where the amount of contamination from partially oxidized fuel is very great.

At least one important European airline operator runs throughout the entire overhaul period of 500 hours without changing the oil, whereas others change only at 75 and 100 hour periods. These figures, it is believed, represent a substantial improvement over those obtained in the United States airlines.

It is of interest, in this connection, to observe the effect of rate of lubricating oil consumption on oil condition, from which the necessity for oil changing is usually judged. With engines of high consumption the amount of oil passing the piston is excessive, and therefore a greater volume of oil becomes partially oxidized on the cylinder walls. Due to the inefficiency of the oil control or scraping arrangements, much of this oxidized material again passes the piston in the reverse direction and contaminates the oil passing through the crankcase. On the other hand, the effect of the additional make-up oil required by engines of high consumption is to reduce the concentration of the sludge, etc. in the oil system of the engine. Generally speaking, however, engines with high oil consumption usually strip in a dirtier condition than those with a low consumption so that control of oil consumption is important for more reasons than one.

In the selection of oils for aircraft engines, the most important property to be considered is that of piston rings sticking. It has long been realized that there is no suitable laboratory test from which the piston ring sticking characteristics of an oil can be predicted. For the testing of lubricating oils it is obvious that a simple test must be devised both from the point of view of cost and economy in time. In cooperation with Messrs. Ricardo & Co. the Shell Company have developed a test using a small motorcycle engine of 250 c.c. capacity (15.2 cubic inches). At 3000 r.p.m. this engine develops approximately 100 b.m.e.p. at full throttle. Cylinder temperatures are controlled by varying the cooling air speed. Still further to increase the severity of the test, fuel is used which gives continuous slight detonation and by a process of trial and error the cylinder temperature can be found at which the lubricating oil under test causes the top piston ring just to stick after a period of 10 hours running. This temperature is used as the criterion in judging lubricating oil for its piston ring sticking property. For the purposes of control and calibration of the engine, a standard oil is used for check tests which are carried out after every three or four tests are made on unknown oils.

An important variable needing control in these tests is the rate of oil consumption. In a short test of his nature, with a high consumption the additional cooling and "washing" effect of the oil behind the piston rings play an important part in reducing the ring sticking tendency of any oil. For this reason, and to eliminate errors which would be due to variations in consumption occurring with oils of different viscosities, the lubrication of the test engine used is carried out on the total loss principle. By this means the

rate of flow of oil to the engine, and therefore its consumption, is under exact control.

Generally speaking, it has been found that the addition of fatty oils to mineral oils results in an appreciable lowering of the ring sticking temperature, but by suitable selection of the various components compounded oils can be produced having piston ring sticking temperatures as high as those of the best generally accepted aviation oils, with the additional advantage that the compounded oils possess of giving freedom from sludge formation.

In this connection, it is very interesting to observe the disparagement with which single-cylinder aero engine tests are regarded in the U. S. A. Some European engine manufacturers consider the results of lubricating oil tests carried out on single-cylinder editions of their full scale engines as giving satisfactory indication of the value of the oil. In fact, it is claimed that it is possible to run the single cylinder under more severe conditions than could be permitted on a full scale unit if the risk of a complete engine failure is to be avoided as far as possible.

The next important characteristics of lubricating oil to be considered are those controlling startability and lubricating oil consumption. These are dependent upon the low temperature and high temperature viscosities respectively. Clearly the viscosity index of the basic mineral oil constituents used for blending compounded oils is of the greatest importance and must be considered in relation to their other essential characteristics. The startability and consumption requirements are in opposition. If consumption alone is considered, high viscosity and good viscosity ratios are essential, although some engines are sensitive to viscosity to the extent that consumption increases after a certain optimum viscosity is reached—apparently this is a function of the oil control arrangements. Experience has shown that oils of 100 to 120 seconds Saybolt at 210°F. are the most popular—the lighter grade being used practically exclusively by European engine manufacturers. Undoubtedly, many of the lubricating oil requirements of engines are better able to be met by the lighter viscosity oils, but this may involve some sacrifice in oil consumption unless improvements in oil control can be effected.

It also appears possible that in engine installations of the future used in high speed aircraft in which the drag of oil coolers becomes increasingly important, some advantage may be gained by increasing the oil outlet temperatures.

To summarize the case for compounded oils for aircraft engine use, it can be said that they can be produced to equal the performance of the best straight mineral oils, and at the same time, offer advantages in regard to cleanliness of running and additional lubricating quality. Thus, they appear to be admirably adapted for use in the high output engines of the future for which fuels will shortly be available and which may suffer from lubrication difficulties on account of the greater loadings (both temperature and friction) which will be imposed upon the main friction surfaces. If it is found that compounded oils are capable of meeting the requirements of the engines of the future, it is clear that existing specifications for oils will need considerable modification, but how best to achieve this introduces many practical difficulties.

Even at the present time lubricating oil specifications are notorious in that while they can be produced to exclude the majority of inferior oils, they frequently result in many oils being excluded which are capable of giving extremely good results in service and most compounded oils come within this category.

There is also one other point which has not been touched upon, that is in connection with the protective qualities of oil, particularly, in those engines using ethylized gasolines. There is no doubt whatever but that materials can be found which, when added to mineral oils improve their protective qualities to such an extent that any fear of cold corrosion under service conditions can be completely eliminated. As yet only the fringe of this subject has been touched upon, but satisfactory methods of simulating conditions to which cylinder barrels are subjected when the engine is laid up for relatively short periods of time (as for instance, in military and naval aviation service), have been developed and already a number of dopes have been produced which are now awaiting extensive trial under service conditions.

In connection with the question of corrosion,

some doubt has been raised as to the desirability of using compounded oils of comparatively high neutralization number in engines employing copper-lead bearings. Whilst it is true that corrosion of these bearings has been observed in automobile engines, it appears to have been entirely absent in aero engines, due, possibly, to the better control of oil changing, etc. in the latter. Moreover, since these troubles originally came to light both materials and method of manufacture have been subject to improvement and with present high quality compounded oils no corrosion whatever should be experienced. Incidentally, some of the European airlines using American engines with copper-lead bearings lubricated with proprietary compounded oils have never reported corrosion of these bearings.

DISCUSSION

S. D. Heron—Ethyl Gasoline Corporation

Mr. Heron referred to the difference in overhaul periods obtained in Europe and America and thought that possibly the longer periods obtained in Europe were due to the fact that lower output engines were in general use. He asked whether the author could give any figures as to the output of the engines on which the performances quoted in the paper were obtained. With regard to the statement in the paper that high lubricating oil consumption makes for dirty engines and ring sticking, Mr. Heron did not agree that this applied to American engines. In general in any given American engine with a given oil, if the oil flow through the engine is increased or the efficiency of the scraper rings reduced, the result is almost always an improvement in general cleanliness of the engine and a reduction of ring sticking.

Mr. Heron was also of the opinion that much higher oil outlet temperatures can be used without harmful effects on stability, as the temperature of the oil dripping from the cylinders was of the order of 500°F. under the most severe conditions. Tests have indicated that it is the maximum temperature that the oil is exposed to in its passage through the engine which has the greatest effect on oil decomposition rather than the inlet temperature.

Mr. Heron also doubted the value of single cylinder engine tests for the testing of lubricating oils unless very thoroughly correlated with a considerable amount of multi-cylinder engine experience.

E. L. Bass

The engines on which the 500/700 hour overhaul periods were obtained were cruising at about 90 to 100 pounds per square inch b.m.e.p. It was not set down as an infallible rule that dirty engines necessarily accompanied high lubricating oil consumption but was a general observation that had been made.

With regard to the use of high oil outlet temperatures, it was agreed that the oil draining from the cylinders may have a temperature of over 400°F. The total quantity of the oil raised to this temperature would only be relatively small in proportion to the whole. With the highly oxidizing atmosphere prevalent in the crank case of the engine, it seemed almost certain that an increased tendency to oxidation would occur if the oil outlet temperatures were raised appreciably above 250°F.

Single cylinder engine tests had been shown by several European engine manufacturers to give quite reliable indication of the quality of oils for their main engines. The usual method of testing was to adjust conditions so that ring sticking would occur at about 50 to 60 hours on a standard oil. The test oil would then be run and the time at which first stages of sticking were observed would be noted. Thus, the ring sticking qualities of the oil could be estimated by the running time obtained.

A. L. Beall, Wright Aeronautical Corporation

Mr. Beall said that some development of suitable lubricating oil tests is very necessary. As far as compounded oils were concerned, the engine manufacturers could not accept any compromise from the standards of startability, oxidation or consumption which they had been accustomed to with mineral oils. This opinion was based on at least 1500 hours of engine testing on various compounded oils.

Mr. Beall said that he already had some knowledge of one or two branded compounded oils which were in use in Europe and which had given excellent results. These had also shown distinct improvement in lubrication from the standpoint of wear.

Full scale engine testing was not altogether satisfactory owing to the large amount of time and trouble which had to be expended. It needed some laboratory test to be developed from which the quality of oils could be determined. No such apparatus appeared to be available at the present time and very little correlation between laboratory results and full scale running had been obtained.

Single cylinder engines usually exaggerated the weakness of oils.

The use of doped oils for the prevention of cold corrosion did not appear very attractive for the reason that corrosion usually occurred on the bare spots on the cylinder which were not covered with an oil film when the engine shut down. It was impossible to hope that any dope would prevent corrosion of those places.

E. L. Bass

One of the important functions of the doped lubricating oil was to enable it to cling tenaciously to the metal and thus eliminate the bare spots referred to by Mr. Beall. It was not intended that the dopes used should provide protection by neutralizing the effect of any acids that were

present but to maintain an oil film which would not be penetrated by the acid.

H. K. Cummings—National Bureau of Standards

Mr. Cummings mentioned that there was a program for lubricating oil research in progress at the National Bureau of Standards which was being carried out on behalf of the Navy. A considerable number of representative lubricating oils are to be run in service engines and subjected to various tests in the laboratory. It was hoped to obtain thereby information as to the value of certain laboratory tests for determining the relative suitability of oils for aircraft engine use. He pointed out that single-cylinder engine tests as well as laboratory tests require correlation with the performance of oils in actual service engines, hence the development of significant laboratory tests was most desirable.

R. F. Gagg—Wright Aeronautical Corporation

Mr. Gagg said that the present situation appeared to be that attempts were being made to combine the advantageous qualities of both mineral and organic lubricants. In the early days of aircraft engines, organic lubricants covered up many of the deficencies of the engine design through the ability of the oil to carry extremely high loads. In more recent history, engines of improved design have been able to run on mineral oils which were in a sense, inferior lubricants but were of extraordinary stability and severe temperature conditions. If the outstanding qualities of the two oils could be combined, a considerable advance would be made. An important factor to be considered is that of startability.

Mr. Gagg referred to the fact that the best laboratory methods of testing available were insufficient, and that little correlation of laboratory results with full scale engine performance was available.

He also said, in regard to the use of single cylinder engines, that were they given the problem of providing a single cylinder test engine primarily for the purpose of reproducing conditions in full scale engines, it could undoubtedly be done. In general, the American attitude in connection with single cylinder engine testing was that it could be regarded as a pilot only.

Mr. Gagg agreed with Mr. Heron that engines with high oil consumption generally have a better appearance in regard to cleanliness than those with low consumption, and he attributed this to the solvent action of the oil referred to in the paper. This introduced the question as to how much oil could be passed by the pistons to produce a clean engine and yet would be economic.

The question of reclaiming oil had to be considered in connection with compounded oils. Many operators use oil reclaimers which it was understood would be quite unsuitable for compounded oils.

E. L. Bass

Generally speaking, oil consumption had a bigger influence on running costs than overhaul periods in airline operation and it did not seem, therefore, that it would be possible, economically, to increase the oil consumption just for the purpose of obtaining cleaner engine and perhaps extending the period between overhauls.

With regard to the reclaiming of compounded oils, it was admitted that many of the systems at present in use would be quite unsuitable, but satisfactory reclaiming was possible by using suitable filters of which certain proprietary makes were available.

Lt. C. F. Coe—Bureau of Aeronautics, U. S. Navy

Lt. Coe referred to the work which was being undertaken by the Bureau of Standards for the Navy, and said that some attempt was being made to correlate laboratory tests for sludging with engine performance. These tests, however, would not include study of piston ring sticking, and apply only to straight mineral oils.

Lt. F. D. Klein—Army Air Corps

Lt. Klein said that the Air Corps had conducted considerable single cylinder engine tests of oils to determine their relative tendencies to deposit carbon and stick piston rings. These tests were made as a basis of correlation with laboratory oxidation tests developed by the Air Corps and elsewhere. It was found that the relative ratings of different types of oils changed when the piston material or jacket temperature were changed, so that actual multi-cylinder data on performance of oils appears to be necessary before any laboratory oxidation method can be shown to be accurate enough to include in oil specifications. Even full scale engine tests unfortunately rate some oils entirely differently, depending on the type of engine and the severity of conditions used. It therefore appears that the only satisfactory method for rating oils for correlation with laboratory oxidation tests involves long-time tests of many types of oils on several types of engines.

The Air Corps has conducted many single-cylinder and some multi-cylinder tests to determine engine friction with varous types of special oils for which considerable reduction in friction was claimed. In all cases it has been found that the engine friction is dependent entirely on the viscosity of the oil. However, wear under high output conditions may vary considerably with different types of oils of the same viscosity. It was found in running a very high output engine that excessive piston ring wear occurred with mineral oil but not with castor oil. Because of the serious gumming properties of castor oil, it is intended to try also a blend of about 5% castor oil in mineral oil, an electrically-polymerized oil, and a graphited oil.

Because of the great cost and time involved in making experimental multi-cylinder tests of oils, there is difficulty in obtaining the necessary amount of data without cooperation by the Navy Department, Air Corps, Bureau of Standards, aircraft engine manufacturers and oil companies. Lacking a cooperative test program, the Air Corps has initiated a system of temporarily obtaining data on the performance of fuels and oils from service activities, the main disadvantage of this method being that oils of very unusual characteristics are not likely to be furnished to the service.

E. L. Bass

There is no doubt but that the most satisfactory way of testing oil was to obtain mass evidence as suggested by Lt. Klein, but obviously such a method had very definite limitations. It was also agreed that engine friction was entirely a function of viscosity whatever claims may be made to the contrary. The additional oiliness of compounded oils did not appear to influence engine friction in the slightest. It was to be expected that tests made with blends containing small quantities of castor oil would be unsatisfactory, due to the fact that the products of oxidation of the castor oil were only soluble in castor oil itself. In the case of the proposed blend, there would be insufficient castor oil to provide any solvent action, and it was quite possible that piston ring sticking would occur even before the time that it occurred with straight castor oil.

D. R. Pye—British Air Ministry

Mr. Pye referred to the fact that the lubricating problems experienced in America appeared to be no nearer solution than they were in England.

In connection with piston ring sticking experiments, Mr. Pye referred to the apparatus developed at the Royal Aircraft Establishment which comprises a cylinder about 3″ long with a 1″ internal bore into which is put a metal ball having a very small clearance. The oil to be tested is put into the cylinder which is then filled with oxygen and sealed and the whole thing is oscillated backwards and forwards in an electric furnace of given temperature. When gumming takes place, the ball sticks and the increased inertia of the whole apparatus is then recorded. This method of testing looks hopeful, but it has been found that such small points as the cleaning of the cylinder before inserting the sample of oil is of paramount importance. Washing with solvents is not sufficient and this aspect of the test is now the subject of further research.

Mr. Pye stressed the point that anything that could be found out in the way of advancing general knowledge on the general lubricating oil problem should be common property, and that as far as work in England was concerned, he was sure that all possible information that was obtained would be passed on.

Elmer Sperry—Sperry Gyroscope Co.

Mr. Sperry said that he thought it very necessary that some explanation be made as to why a compounded oil performs better than the base oil alone. Since the lubricating quality of an oil depends upon its chemical properties for stability and on its film strength for load carrying ability, a complete report of a successful compounded oil should state how the compound affects these characteristics. Perhaps the most important effect of a compound is to increase the ability of the oil to cling to metal or to form a substantial boundary layer, but this is beyond the scope of the oil chemists and engineers. Therefore, the superiority of compounded oils will not be understood until the molecular theory of the physicists is given more credence.

Dr. D. P. Barnard—Standard Oil of Indiana

The difficulty now standing in the way of the development of a suitable test procedure for appraising the stability characteristics of aviation engine oils consists in the lack of a clear-cut and sufficiently complete service background. Such a background should consist of a series of oils covering the entire range of stability for which general agreement has been reached as to the exact relative position of each individual lubricant. If such a service basis could be provided the development of a laboratory method which would place these reference oils in their correct relative positions would be a comparatively simple matter. Until the time, however, that such a service background can be provided, attempts to develop laboratory appraisal methods can be little more than individual guesses.

W. A. Parkin—Pratt & Whitney Aircraft Company

The three most serious problems to be considered were cylinder wear, ring sticking and sludge formation in crankcase but it did not appear that these became very serious until take-off powers over 160 pounds per square inch b.m.e.p. and cruising powers of 120 pounds per square inch b.m.e.p. were reached. For example, no troubles were experienced on the original C1 Wasp rated at 420 hp. but when the rating was raised to 550 hp. and the engine cruised at 420 hp. lubrication difficulties were experienced.

Piston ring stick had been generally cured by increasing the circulation of the oil in crankcase and this had already resulted in better cooling which had helped to reduce sludging.

Mr. Parkin did not agree with the statement made by Mr. Heron that excessive sludge formation in the crankcase was not harmful. He knew of several occasions when forced landings had occurred due to plugging of oil channels by sludge. It was to be hoped that the use of compounded oils would help considerably in reducing the cylinder wear problem.

Mr. Parkin said that he thought the single cylinder engine might be used for development purposes but as yet it had not been possible to obtain satisfactory correlation between single cylinder and full scale engines operating in the field.

Mr. N. F. Larsen of the Sinclair Refining Co., Mr. Neal MacCoull of the Texas Company, Mr. E. Aldrin of the Standard Oil of New Jersey, Dr. Haskell of the Texas Company, and Mr. Leon Cammen of the A.S.M.E. also contributed to the discussion.

Institute Notes

Honorary Fellow for 1935

Dr. William F. Durand has been elected by the Fellows of the I. Ae. S. an Honorary Fellow of the Institute "For his contributions to hydrodynamics, thermodynamics, and aerodynamics, particularly with relation to the advancement of the knowledge of air propellers. For his supervision of a review of the development of aerodynamic theory since flight in heavier-than-air craft became an assured fact."

Dr. Durand graduated from the U. S. Naval Academy in 1880. He received, from Lafayette College, the degree of Doctor of Philosophy in 1880, and Doctor of Laws from the University of California in 1927. He was Professor of Mechanical Engineering at Cornell and Leland Stanford Universities and is now Professor Emeritus at Leland Stanford University.

He was appointed by President Wilson in 1915 one of the original twelve members of the National Advisory Committee for Aeronautics and was elected Chairman in 1916, and served continuously on the Committee until 1933. During the War he was scientific attaché to the American Embassy in Paris and member of the Interallied Commission on Inventions. He was a member of the President's Aircraft Board in 1925. From 1926 to 1930 he was a trustee of the Guggenheim Fund for the Promotion of Aeronautics. He has been awarded the Guggenheim Medal for distinguished aeronautical achievement for 1935. He is now Editor-in-Chief of "Aerodynamic Theory," which is being published in six volumes.

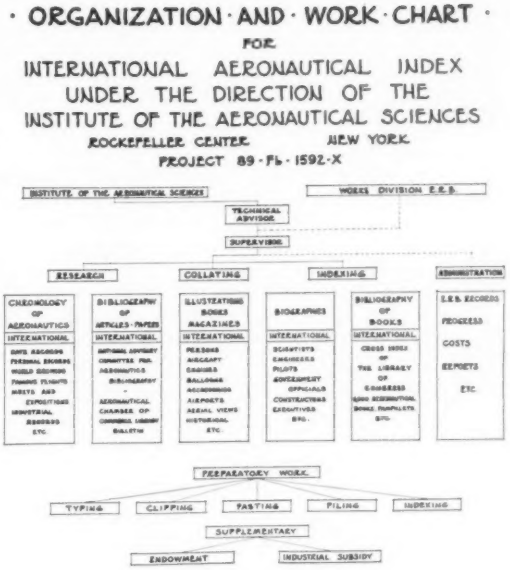
Addition to the Institute's Aeronautical Index

The work of preparation of the Index is to be greatly expedited in July by the Works Division of the Emergency Relief Bureau of the City of New York, which has increased the number of workers to twenty-five.

The organization chart shows the divisions of the Index, but a valuable addition has been made through a generous donation by Luis de Florez of $250. This has permitted the purchase of *The Engineering Index* which is issued annually, each volume containing about 1200 pages. This index reviews and digests the engineering and scientific articles and papers appearing in over 2000 publications. The 1934 edition contains 40,000 descriptive references to articles, papers, and reports. By this gift of the Index since 1926 the Institute has available for the use of members over 350,000 digested references, not only covering the aeronautical field but all the other branches of engineering. The Council of the Institute has expressed to Mr. de Florez their appreciation for making available this service to members.

The Index now has nearly 90,000 cards in its files, and this will be increased to 200,000 by the end of the year.

In addition to the Index a Chronology of Aeronautics is being prepared. Members and organizations have been requested to add to this Chronology by furnishing the chronologies of their specialties. Already the leading published chronologies have been consolidated and cross referenced. Later, it is hoped that the discrepencies may be corrected by research, and a series of pamphlets covering specialized fields may be printed. In this way any inaccuracies which are inevitable in such a compilation may be checked by specialists in each field. Eventually, it is hoped to publish a consolidated Chronology which will be comprehensive and cover all the principle activities in aeronautics from legendary times.



National Advisory Committee for Aeronautics Tenth Annual Aircraft Engineering Research Conference

This year's conference was held at the Langley Memorial Laboratory at Langley Field, Virginia, on May 22.

In attendance, there were 152 members of the Institute among the visiting group and 26 other members who are engaged in the work of the N.A.C.A.

The customary routine of a preliminary description of what the visitors were to be shown, visits to the laboratories, lunch and afternoon sessions giving the results of the research work of the past year in various fields was followed.

Twenty-five Years for Sperry

All aeronautical specialists will congratulate the organization founded by the late Dr. Elmer A. Sperry on its completion of twenty-five years of notable engineering service. The word "gyroscope" and the name Sperry have become synonymous. The application of the gyroscope

to aeronautical instruments has made it a practical utility for airmen. The pioneering work on early aircraft of Lawrence B. Sperry, son of the founder of the company, has made his memory one of the most notable among the early pilots and constructors. The Sperry Company was one of the earliest Benefactors of the Institute and all members will wish it many years of continuing successful progress.

Suggestions for Contributors

The Editorial Board of the Institute of the Aeronautical Sciences has compiled valuable information for Contributors to the Journal of the Aeronautical Sciences from leading sources of technical information, using the makeup of the Journal as a standard.

All authors contemplating the preparation of papers for consideration in the Journal are urged to write for their copy of these "Suggestions."

Condensed information is given as to: Style, Preparation, Titles, Biographies, Summaries or Abstracts, Sub-Headings, Matter usually deleted, References and Footnotes, Illustrations, Captions and Legends, Mathematical Expressions, Correct form of Abbreviations, Proofs, Postage, Reprints.

Lighter-Than-Air Craft Forum

The Daniel Guggenheim Airship Institute and the University of Akron announce a forum on lighter-than-air craft to be held at the Airship Institute at Akron, Ohio, on July 25th and 26th.

The object of the forum is to review the present status of lighter-than-air craft development from the engineering and scientific standpoint. A number of experts and specialists in various branches of the subject will be present, among them members of the Committee for the Investigation of Lighter-Than-Air Craft, appointed by the Secretary of the Navy.

A program and registration card will be sent to those who make the request to Dr. Th. Troller, Daniel Guggenheim Airship Institute, Akron, Ohio.

Meeting of Pacific Coast Section

The second meeting of the Pacific Coast Section of the I. Ae. S. was held at the California Institute of Technology. About 100 members and guests attended. A program committee was appointed with the following membership: C. L. Johnson, Carl Stryker, W. B. Oswald, N. B. Moore, and W. C. Rockefeller. Mr. Johnson was appointed Chairman.

Three papers were read, digests of which follow:

BRUCE BURNS

The Northrop Corporation

Aircraft Spot Welding. This paper first outlines the elementary requirements of a spot welding machine suitable for general purpose aircraft spot welding, and discusses the general process of making a spot weld.

Macrophotographs are presented showing sections through spot welds in various aluminum alloys, accompanied by a discussion of variation in welding conditions and their influence upon size, shape and quality of the spot weld. A chart is presented showing the relations existing between sheet thickness, amount of current, time of current application and electrode pressure.

Several macrophotographs show the effect of deviation from optimum conditions and the result of careless shop practice. The point is stressed that for uniform production results the material to be welded must be in uniform surface condition.

Macrophotographs of tensile and fatigue test specimens after failure are shown, with curves of typical static and fatigue test values. Conservative design values for static and fatigue conditions are derived. Typical drafting room information is given.

A short discussion of present and possible future uses of spot welding in aircraft construction concludes the paper.

C. E. STRYKER

Curtiss Wright Technical Institute

Stress Analysis Problems. The paper is a collection of ideas from various sources with the purpose of starting discussion especially in regard to Bulletin 7A. The order of analysis is changed and some helpful data omitted. Published airfoil data are conflicting although necessary in the stress work now. Different requirements are needed for different types of aircraft. Although an airspeed indicator is not now required, a 1% variation in speed can cause a 0.7% variation in design factor. Loads applied to flight maneuvers are based on tests several years old, do not take the control effectiveness into consideration, and use the hp. to the .435 power. Loads determined from gust conditions use the hp. to the ⅓ power. The modern airplane shows the fuselage to have effective lift. The new tail surface loads seem unduly severe for the light aircraft. A comparison of the methods used to determine applied loads in stressed skin construction show good uniformity, but calculation of allowable loads does not seem to agree due to lack of comparison of data.

Discussion of Mr. Stryker's Paper, Including Comments by Mr. E. A. Peterman of the Dept. of Commerce, Aeronautics Branch.

A change in F.S. was urged which would aid export agreements. Western manufacturers should take more part in advising on changes in requirements. If the airspeed were specified and checked and the "possible power curve" for a given airplane approved, it would be possible to allow considerable leeway in the engine which could be installed. Max. C_N should be limited and tail surface loadings clarified. Fuselage lift is acceptable on basis of wind tunnel.

HAROLD ADAMS

Douglas Aircraft Company

Airplane Hydraulic Systems. (Abstract prepared by W. C. Rockefeller.) Mr. Adams, in a paper entitled "Airplane Hydraulic Systems." presented many of the problems encountered in hydraulic installations. In the paper he subdivided the applications into five different types which have been used to date: the engine oil system (controllable propeller), the constant pressure system (continuous pumping), hydraulic brakes, closed systems (experimental surface controls), and the general hydraulic system operating landing gear, wing flaps, etc. He considered the layout of the basic system which is found on all the aircraft, independent of size. Many of the details of standard units were considered, together with the problems and difficulties they presented. Finally he summarized the advantages and disadvantages of hydraulic systems as compared with other types, and considered the probable extension of these systems to other applications.

Honors

Igor Sikorsky was given the honorary degree of Doctor of Science by Yale University on June 19.

The citation for the honor follows:

Professor Nettleton—A pioneer in the science of aviation and in the art of invention, early identified with his native Russia; since the war, a citizen of the United States and of Connecticut, and by virtue of his supreme contributions to the practice of international air transportation and to the principles of international cooperation and friendship, a citizen of the world. At the age of 19, building his first aircraft; at 23, twice winning foremost honors in open competition with the leaders in airplane design; at 24, building and flying the world's first multi-motored airplane; in peace, and in the emergency of war, he gave to his country the youth of his constructive genius. To America he has brought, with the full maturity of his creative powers, the realization of his own world-wide vision, which "saw the heavens fill with commerce, argosies of magic sails." His recent argosies are significantly named Pan-American "Clippers." His giant Brazilian Clipper has become a symbol of American enterprise and of Pan-American accord. His line has gone out to the end of the earth—herald of friendly conquest of the Pacific. "Peace hath her victories."

President Angell—Brilliant contributor to man's mastery of the air, skilled and resourceful designer of ships which link continent to continent in swift new bonds of friendship, Yale University, in recognition of your remarkable achievement, confers upon you the degree of Master of Science, admitting you to all its rights and privileges.

Dr. Alexander Klemin, Director of the Daniel Guggenheim School of Aeronautics of New York University, and a Scientific Member of the Institute, was given the degree of LL.D., at Kenyon College, Gambier, Ohio, for "contributions to the science of aeronautics."

Lecture by Captain E. C. Johnston

Captain E. C. Johnston, Controller of Civil Aviation of the Australian Commonwealth, was guest speaker at a dinner given in his honor by the New York members of the Institute at the Columbia University Faculty Club on Thursday, May 16. Charles L. Lawrance presided. D. M. Dow, official Secretary for Australia in the United States attended and expressed his appreciation for the courtesy that was being shown Captain Johnston.

Captain Johnston enlisted with the Australian Imperial Forces in April, 1915. He served in Gallipoli and France. He is credited officially with the destruction of seven enemy planes. Captain Johnston joined the Civil Aviation Branch of the Australian Department of Defense in 1921 and in 1933 was appointed Controller of Civil Aviation. He is making a tour of the world visiting the aeronautical centers of many countries.

In his address he gave a history of civil aviation in Australia and the development of the air transport network of airlines. Seventy members of the Institute heard Captain Johnston describe the National Australian Aeria Medical Service which is unique. It was started by the Rev. John Flynn, a Presbyterian missionary who has dedicated his life to the people "Out Back," the ranchmen and sheep herders whose isolated homes are located in the interior of the great inland continent and away from the main lines of transport.

Before this service was started they received their mail three times a year. Medical attention was formerly unavailable. Through the efforts of the missionary the Australian government placed radio transmitters at many places which could be operated by a typewriter keyboard—the power being furnished by a bicycle pedal device. Replies were received by the usual voice receivers. At several hospitals physicians were on duty at all times to receive calls from these transmitters. If the ailment was minor a treatment would be prescribed over the voice transmitter. If the patient could not be treated at his home he was flown to the nearest hospital.

Book Reviews

By R. Paul Harrington

Structural Design of Metal Airplanes, by John E. Younger, McGraw-Hill, 1935, 344 pages, $4.00.

Professor Younger, assisted by Mr. Raymond H. Rice and Professor Nairne F. Ward, has presented in this text the fundamental principles and methods involved in the metal construction of airplanes. Due to the phenomenal strides in all-metal plane construction in the last few years, text books on design have fallen far behind in this respect. Hence Professor Younger's offering stands alone as the only book covering this latest phase of airplane development. The problem is treated in four sections.

Section I presents briefly and adequately the design requirements; the calculation of loads and load factors, for which free body sketches and the development of the equations are included; and general design procedure.

The materials available for construction are covered in Section II by Professor Ward. This is a concise summary of the classification of alloys, both ferrous and non-ferrous; the modification of the properties of metals durin fabrication, a very important consideration; and finally corrosion and methods for prevention.

Sections III and IV occupy by far the greater bulk of the book. The former, entitled "Basic Structural Analysis" presents the applications of mechanics to the design problems in a surprisingly thorough manner, and entails the treatment of statically determinant and indeterminant structures, the properties of plane sections, beams and struts under various loadings. continuous beam columns, and torsion.

The final section attacks the special problems pertinent to the design and construction of metal airplanes, with special attention to cantilever wings and wing flutter. Short chapters discuss riveting and welding in aircraft construction, and the stress analysis of landing gear.

The book is in a form admirably suited as a text for college students, but by no means limited solely to that field. It has been written in a direct manner and shows that a tremendous amount of condensation of material had been done. Each chapter is accompanied by a generous list of references, sketches, and current illustrations.

Due to its wealth of new material and its refreshing style it is highly recommended.

Technical Aerodynamics, by K. D. Wood; Cornell Co-Op Society, Cornell University, 1934; 280 pages, 230 figures, mimeographed and lithographed, $3.00.

This is the second of a series of three books on aerodynamics and airplane design by Professor Wood, Professor of Engineering at Cornell University and consulting engineer. He presents in a condensed form and with a minimum of descriptive material the elements of aerodynamics as applicable to airplane stability and performance calculations.

The presentation is direct and has a logical sequence which makes it a text of more than average value for students in technical aerodynamics. The eleven chapters cover recent developments in airfoil theory, parasite drag estimates, the latest propeller data, stability calculations, a discussion of hulls and floats, and well explained charts for rapid estimate of airplane performance by Oswald's method. Subordinate subjects and some problems are also included.

A valuable addition to the book is the unusually lengthy appendix which is a compilation of the more important N.A.C.A. and other current data, presented in the same general order as the subject matter in the text in curves and tabulated forms.

In the mimeographed form the book is fairly difficult reading and a number of errors are noted which however, appear to be rapidly decreasing in number with each printing. The printed edition in regular book form will be available in August 1935, published by McGraw-Hill.

Airplane Design, by K. D. Wood; Cornell Co-Op Society, Cornell University, 1934; 380 pages, 300 figures, mimeographed and lithographed, $4.00.

The fundamental aerodynamics set forth in "Technical Aerodynamics" by the same author (reviewed above), are applied to the design of airplanes in this book which fills a particular gap in the text book field. The same directness encountered in the preceding book is carried along to a considerable extent in this presentation.

The subject matter first covers layout calculations, load factors, materials and costs, and later presents the principles of design and stress analysis pertaining to wings, landing gear, control surfaces, fuselages, and hulls and floats. Sample calculations and some problems are included.

The book does not cover in detail all the principles of mechanics entailed in other texts to which references are made. The problems encountered in design and the method of attack are quite clearly indicated.

At least half of the book is another lengthy appendix containing many sketches, photographs and tabulated data pertaining to the weight of equipment, costs, and materials of construction. Indexed copies of Aeronautics Bulletins Nos. 7A and 26 are included, together with sample computations and graphical representations of design equations.

The mimeographing again presents its difficulties to readers and several philosophical remarks detract from the value of the book as a text. It seems that more information in regard to the design of monocoque fuselages would be a welcome addition.

Membership of the Institute

Since the publication of the last Membership Roster in October 1934, at which time the membership of the Institute was 883, the membership has increased to 1,063.

Below will be found the additions to membership and the losses due to death, resignation, and other causes.

NEW MEMBERS

Adamson, R. M.
Aiken, Jack F.
Allen, Hugh E.
Allen, H. Julian
Allward, George A.
Andrews, W. I.
Arisaki, Ryohei
Arnold, Weld
Ashton, B. N., Jr.
Assessor, A. J., Jr.
Babberger, Carl
Baker, Ralph D.
Bass, E. L.
Bassett, Lieut. Charles A.
Bates, C. I.
Bates, M. F.
Beakley, Lt. Wallace M. (U.S.N.)
Bell, Earl O.
Beren, Homer
Bergh, Roland C.
Berke, Harold
Bernstein, Edwin J., Jr.
Bockius, Lt. R. W. (U.S.N.)
Bollay, William
Bonfoey, L. P.
Boughton, W. V.
Bowen, Wm. H.
Brady, George W.
Brinker, Edwin C.
Brown, Ray W.
Burton, Edward F.
Carr, Gardner W.
Cassese, Salvatore
Cassidy, Edward T.
Cassidy, William J.
Charters, Alex C.
Cheney, H. K.
Childers, Milford C.
Clauser, F. H.
Clements, N. V.
Clyne, James W.
Colman, Philip A.
Cox, J. W.
Dane, Paul H.
Davidsen, S. W.
Den Hartog, Dr. J. P.
Dick, N. R.
Dods, J. P.
Doyle, Michael A.
Dunning, A. W.
Eichler, Ed.
Erickson, Robert I.
Evans, Stanley H.
Eveleth, E. Lincoln
Faile, E. H.
Ferrari, Ing. Carlo
Fitz, J. A.
Fletcher, Robert Dawson
Forman, George R.
Foster, Edward E.
Foster, William H.
Fraim, J. P., Jr.
Frecking, George F., Jr.
Fritz, L. G.
Frye, Jack
Galantowicz, E. P.
Glasgow, Charles, Jr.
Glowa, Latimer W.
Goldsmith, Gustave M., Jr.
Gough, Melvin N.
Gray, J. T.
Grube, Karl P.
Gruber, F. M.
Gureasko, Edward M.
Halli, Robert W.
Hanajima, Rear Adm. K.
Harmon, Hubert N.
Harney, Pat J.
Harrington, R. P.
Hashimoto, Prof. K.
Haskell, Dr. Raymond
Haworth, Harold H.
Haynes, Ben C.
Heatley, James J.
Herschede, Frank C.
Holbrook, D. L.
Howland, W. Lavern
Hutton, Richard
Ireland, G. S.
Jacobs, Richard O.
Jenny, Cletus J.
Jenny, William
Jensen, Ernest V.
Johnson, Clarence L.
Johnson, William
Karl, William C.
Katzenstein, Richard
Keiser, R. K.
Kelly, Thomas N.
Kidder, Robert C.
Kirschner, Paul
Knobcock, F. D.
Kollsman, Paul
Koolhoven, Frederik
Frenz, E. J.
Kuethe, Dr. Arnold M.
Kumpera, Dipl. Ing. Teny
Lacy, R. H.
Laing, Robert W.
Lankin, Wm.
Latham, Ray L.
Lau, Alfred H.
Leisy, C. J.
Lemke, George A.
Lindner, Robert H.
Lindsay, K. S.
Lowry, Edmund G.
Lutz, Frederick W.
McBeth, Carrol R.
McBrearty, Jerome F.
McCoy, Lieut. H. M.
McDonnell, J. A.
McKay, Walter
McManness, J. W.
Madelung, Prof. Georg
Majneri, Ludwig A.
Malina, Frank J.
Maloy, R. B.
Marsh, Herbert
Martin, V. J.
Masland, William M.
Medland, Paul A.
Melick, Paul K.
Merkel, Otto J.
Messiner, G. W.
MeVay, Francis
Mills, R. H.
Montieth, Oscar
Moore-Brabazon, Lt. Col. J. T. C.
Moores, R. C.
Moorhead, Robert C.
Morris, John K.
Moseley, C. C.
Moy, Stanley
Nakanishi, Prof. E.
Neumark, Dr. S.
Niccolls, R. S.
Nicoll, Major Reginald E.
Nordlinger, Lieut. S. G.
Ogawa, Prof. T.
Ono, M.
Otto, B. R.
Pahl, John F.
Palmer, Richard W.
Parkinson, J. B.
Parks, Oliver L.
Parr, Lt. Warren S. (U.S.N.)
Peay, Edmund R.
Peck, Wm. C.
Penton, Paul
Petry, Stanton H.
Pianowski, Leon J.
Powell, Mortimer
Powers, Vincent J.
Prager, Prof. Dr. W.
Proebstle, L.
Pusin, Herman
Reff, E. Robert
Reid, C. T.
Rhines, Thomas B.
Richter, Paul E.
Ricketts, D. H.
Ritchie, Perry Jr.
Robbins, Richard W.
Robie, Charles F.
Robinson, S. T.
Rogallo, Francis M.
Rohrbach, Dr. Adolf K.
Root, L. E.
Ross, J. J.
Russell, Lt. J. S. (U.S.N.)
Rybeck, Jerry
Ryder, Edmund L.
Savoja, Dr. Ing. U.
Sayre, Daniel
Schaal, Ellsworth A.
Schweikart, H. C.
Sears, W. R.
Sechler, Dr. E. E.
Sefcsik, Louis J.
Sezawa, Prof. K.
Shannon, Owen
Sheridan, Dr. Laurence W.
Shorr, Melvin
Shumowsky, S. A.
Simons, Bernard J.
Sinclair, C. E.
Slaughter, Dick
Smith, Alden F.
Soellner, Rudolf
Somers, F. P.
Squiers, John C.
Stafford, P. H.
Stephens, Boyd C.
Stout, Joe W., Jr.
Sullivan, Thomas M.
Szczepanski, Ray J.
Taliaferro, A. P., Jr.
Terazawa, Prof. K.
Thibodeau, Robert E.
Thomas, Chas. F.
Timoshenko, Prof. S.
Tweney, George H.
Van Stone, T. C.
Viets, William
Vultee, Gerard F.
Wada, Prof. K.
Wagner, Raymond P.
Walter, Gerald L.
Watter, Dr. Michael
Weber, Clinton L.
Weitekamp, Elmer J.
Welch, N. A.
Welles, J. A.
White, Roland J.
Wiebe, Albert I.
Wood, Carlos
Wood, Louvan E.
Woodelton, Roy B.
Wright, John A.
Yeomans, John H.
Young, B. H.
Young, Don W.
Zelcer, F. William
Zinn, Rahland
Zimmermann, B.
Zuckerberg, Harry

DECEASED

Hoyt, Richard F.
Junkers, Prof. Hugo

RESIGNED

Emmons, H. H.
Findley, Earl N.
Haslam, R. T.
Kearney, Norman L.
Osborn, Earl P.
Trumbull, John H.
Westervelt, George C.

NO LONGER MEMBERS

(See Sec. 7, Art. II, By-Laws)

Brimhall, Dean R.
Carroll, Thomas
Chamberlin, C. D.
Champion, C. C.
Diamond, James E.
Fenn, E. H.
Gardner, Grandison
Gaylord, R. P.
Halsted, Arthur
Havill, C. H.
Hewlett, R. C.
Hill, C. G.
Hoover, Herbert, Jr.
Hurley, Roy T.
Maag, Geo. A.
Olbeter, Max T.
Preston, C. I.
Rasmussen, S. A. U.
Richardson, F. E.
Schlosser, A. G.
Schroeder, R. W.
Taylor, Wm. H.
Towle, Tom
Van Heuckeroth, A. W.
Vosler, K. D.
Weihmiller, H. E.
Williams, Harvey L.
Young, Wm. C.

Books Received

Axialgebläse vom Standpunkt der Tragflügeltheorie, by Dr. C. KELLER, A. G. Gebr. Leemann & Co., Zurich, 1934, 187 pages.

Journeés Scientifiques et Techniques de Mécanique des Fluids, ÉTIENNE CHIRON, Paris, 1935, Two Volumes, 428 and 390 pages respectively. Proceedings of a meeting of L'Institut de Mécanique des Fluides, held at the University of Lille, France.

Principles of Aerodynamics, DR. MAX M. MUNK, Washington, D. C., 1933. Presented by the author.

The Flying Machine, DR. F. W. LANCHESTER, Constable & Company Limited, London, 1918, 135 pages. Presented by the author.

Aircraft in Warfare, DR. F. W. LANCHESTER, Constable & Company Limited, London, 1916, 222 pages. Presented by the author.

An Explorer in the Air Service, HIRAM BINGHAM, Yale University Press, 1920, 260 pages. Presented by the author.

Junior Aircraft Year Book, Aeronautical Chamber of Commerce of America, New York, 1935, 255 pages. Parts of the larger Aircraft Year Book and of interest to young people.

Stratosphere and Rocket Flight, CHARLES G. PHILP, Sir Isaac Pitman & Sons, London, 1935, 106 pages; $1.25. A popular handbook on Space Flight of the Future, including a section on the problems of interplanetary space navigation.

The Aircraft Year Book, Aeronautical Chamber of Commerce of America, New York, 1935, 538 pages, $3.50. The standard record of American aëronautical progress. An annual review of the progress of the aircraft development in the United States. It gives a yearly chronology, records and personnel of aviation.

Apparatus Notes

The Pratt & Whitney Aircraft Company, of East Hartford, Connecticut, has developed a new, single-unit, Automatic Power & Mixture Control.

This unit, by maintaining a constant density of the air entering the carburetor, produces a practically constant fuel-air ratio delivered to the carburetor through the normal operating range.

With a constant speed propeller, power regulation equivalent to any device maintaining constant manifold pressure is obtained.

The Cannon Electric Development Company, of Los Angeles, California, has produced a new design of ground battery plug and receptacle for airplanes. The original unit had prongs on the battery cart fitting and sockets on the ship. However, if an operator carelessly left the switch closed on the battery cart, it could burn a hole in the skin of the ship with projecting prongs which would be hot. To offset this the company is now building the unit in reverse with a dead-front receptacle unit on the battery cart and a prong unit in the ship, which is so arranged that the prongs are above the surface and nothing is projecting. Adapters are also produced that make it possible to use either type on any ship equipped with the Cannon fitting.

The Pioneer Instrument Company, of Brooklyn, New York, has developed a new Ring Light in which light is conducted through a curved glass rod which encircles the dial.

The operation of aircraft when light is unfavorable for reading instruments makes the problem of illumination one of great importance. Especially at dawn and dusk it has been found that luminous treatment of the dial alone is not completely satisfactory and that a secondary lighting system must be employed.

Ring Lights can be built into the cases or new instruments, or can be installed on any standard instrument of any make.

THE THIRD PILOT *flys* THE PLANE

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ROTTERDAM, May the 14th 1935.
VLIEGVELD: WAALHAVEN

No. 3986.DR.HM.TD.240
Betr. Propellers.
From the Chief Engineer K.L.M.
To Hamilton Standard Propeller Company
Hartford,Connecticut U.S.A.

Gentlemen :

According to your request we now can give you the following information regarding our experience with the Hamilton Standard controllable propeller,which we bought from you.

At the present moment we have in use or on order a total amount of 102 controllable propellers i.e.: 62 Wasp propellers, 3 propellers for direct drive Cyclones and 37 three-bladed propellers for geared Cyclone engines.

With 59 controllable Wasp propellers we have reached a total number of 60.000 hours. Our oldest airscrew has been used up till now 2000 hours. This propeller was delivered to us in September 1933 and it was first used for about 600 hours on a Fokker F 12 aeroplane on our European lines, which now make connections between Amsterdam, Rotterdam, Copenhague, Hamburg, Berlin, Frankfort, London, Liverpool, Hull, Brussels, Paris, Essen, Halle-Leipzig, Praag and so on. In May 1934 this same propeller was mounted on one of our Fokker F 18 aeroplanes and it was used on our well-known line from Amsterdam to Batavia, where it has been used up till now.

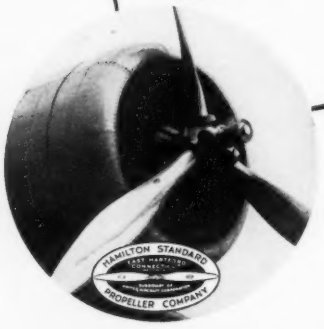
It will interest you to learn that we have covered in total about 4 millions of kilometers with the use of your controllable propellers and that we have experienced during this time that the propeller stands very well every weather condition in Europe, such as rain, hail and heavy storms, as well as the heavy monsoons and dust storms,which are encountered under the tropical conditions on our Indian line.

Regular inspection is done every 200 hours and in several cases the time between these periods may be easily increased to 300 hours. Maintenance of controllable propellers could be reduced considerably and only very few new parts are required. A complete overhaul is done by one man in about 12 hours time.

We are pleased to say that we have stated that the Hamilton Standard controllable propeller has shown to be reliable and that we have the impression that it makes every modern aeroplane safer and more economical, whereas during 60.000 hours of service there was not a single moment that one of your controllable propellers did not give full satisfaction.

Yours faithfully,

(P.Guilonard/Chief T.D.)

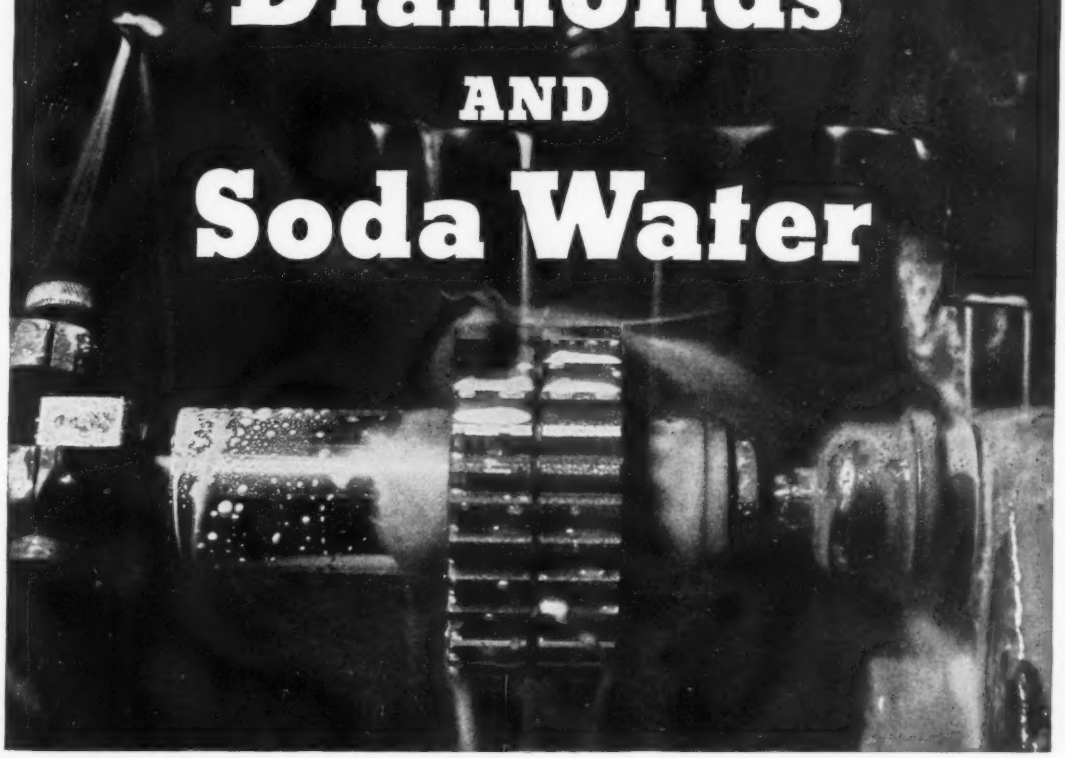


K. L. M. one of the world's outstanding airlines, has placed its seal of approval on Hamilton Standard Controllables. 102 of these propellers now installed on the planes of the Royal Dutch Airlines are providing satisfactory service under varied conditions of operation from Holland to Java.

HAMILTON STANDARD PROPELLER COMPANY • EAST HARTFORD, CONNECTICUT

Jobs that help build the Pratt & Whitney Reputation for Dependability

Diamonds AND Soda Water



It took considerable ingenuity, long hours of experimenting before the Pratt & Whitney technical staff found a way to make gears better than they had ever been made before. But a machine was devised which, under a deluge of soda-water, produces gears with teeth absolutely true and accurate to within two ten-thousandths of an inch. The edge of the special grinding wheel responsible for this perfection is dressed with diamonds to an exact angle twice during the grinding of each gear.

It is typical of Pratt & Whitney standards that this, and other operations are performed the hard way for the sake of better workmanship. The teeth of many of these Wasp and Hornet gears are too hard to machine with even the finest of tool steel. They have to be to stand up at speeds as high as 31,000 r.p.m. Pratt & Whitney engineers cannot be satisfied with gears produced by any process other than the most exacting.

The painstaking care and extra hours needed to set up one of these machines is more than justified by the outstanding record for dependable performance that has made the Pratt & Whitney escutcheon a familiar, trusted trade mark wherever private, commercial and military aircraft are in service.

WASP & HORNET ENGINES

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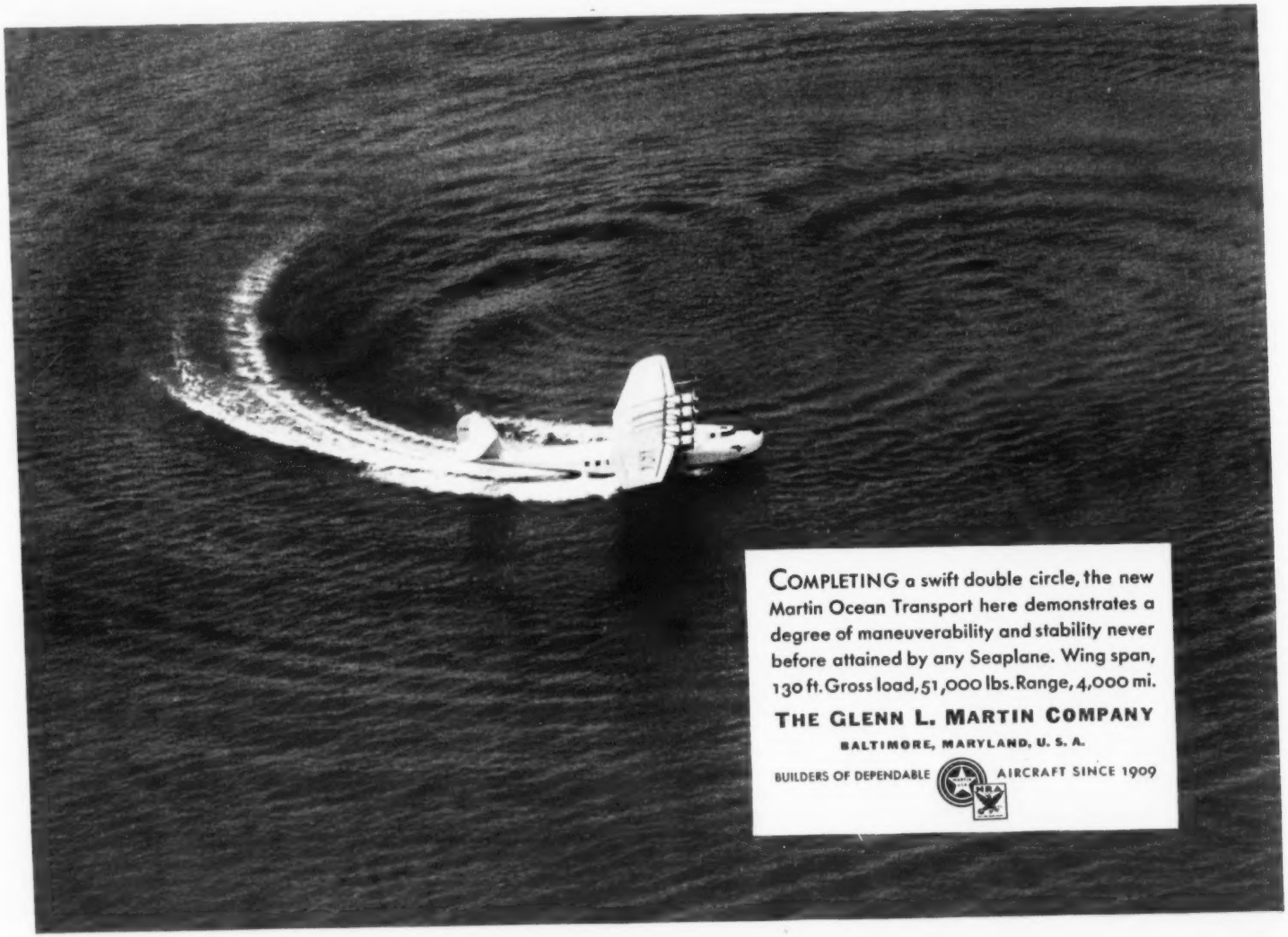

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BRAKE WHEELS

High and Low Pressure—"Streamline"

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TAIL WHEELS

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AXLES

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BRAKES

Mechanical and Hydraulic

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TAIL WHEEL KNUCKLES

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PNEUDRAULIC SHOCK STRUTS

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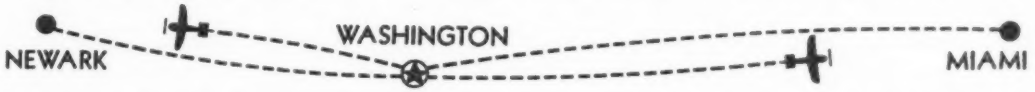

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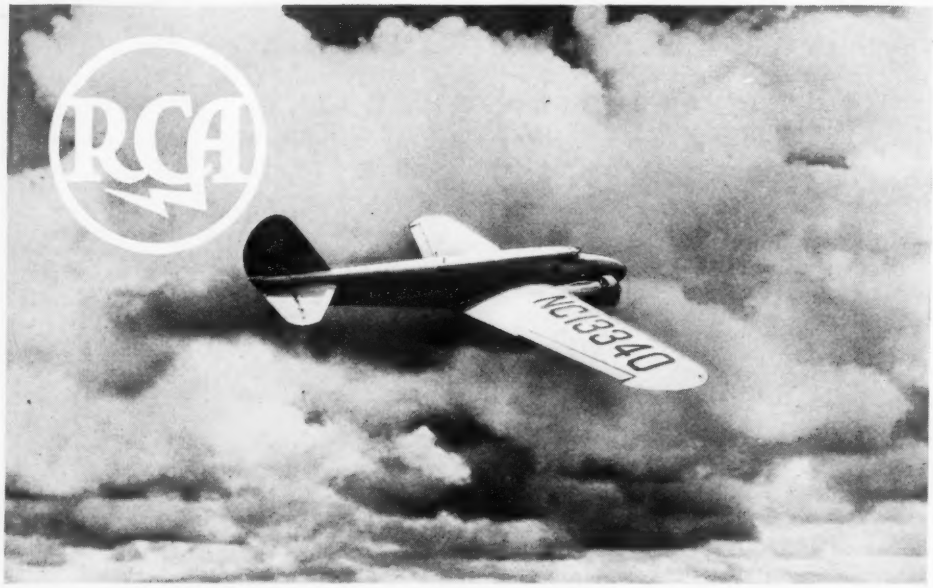

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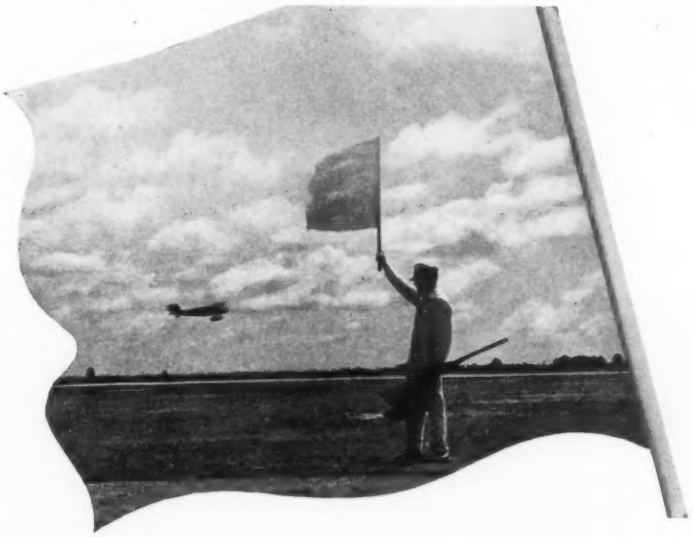

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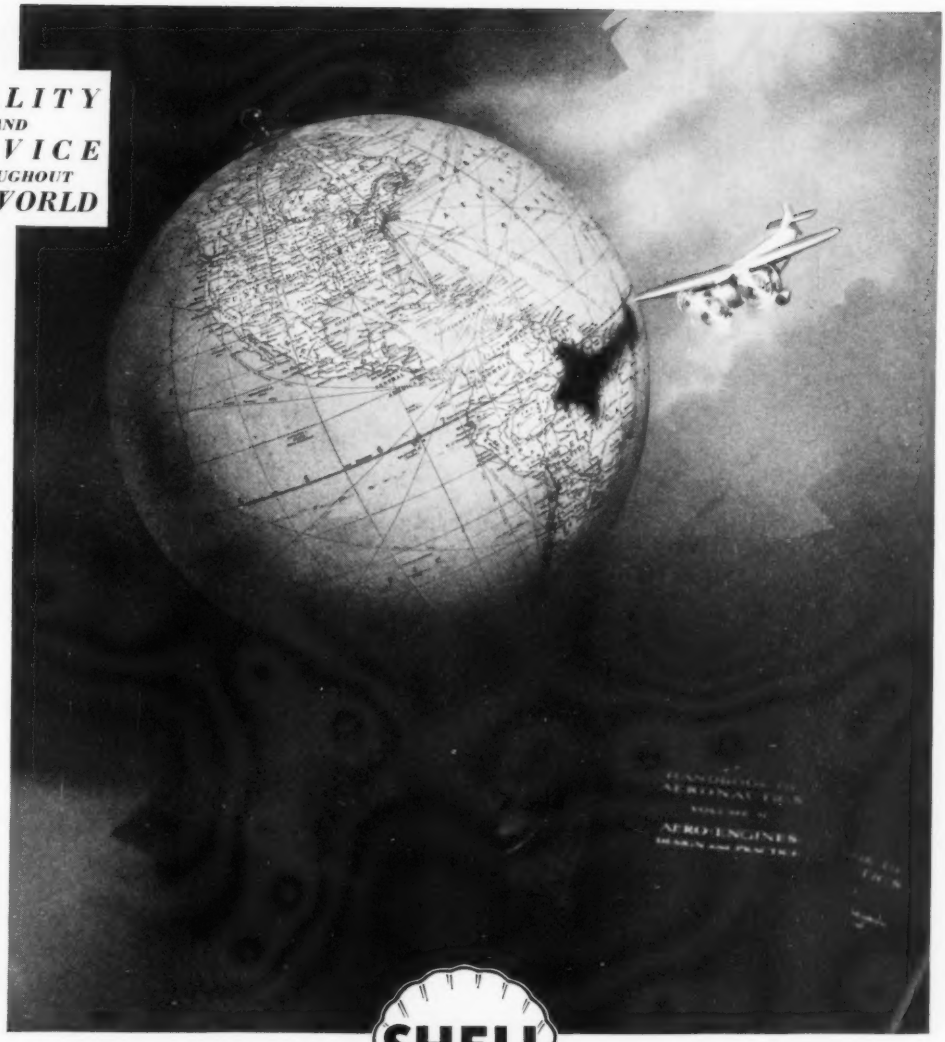

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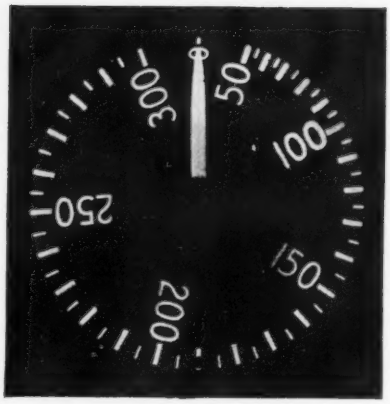

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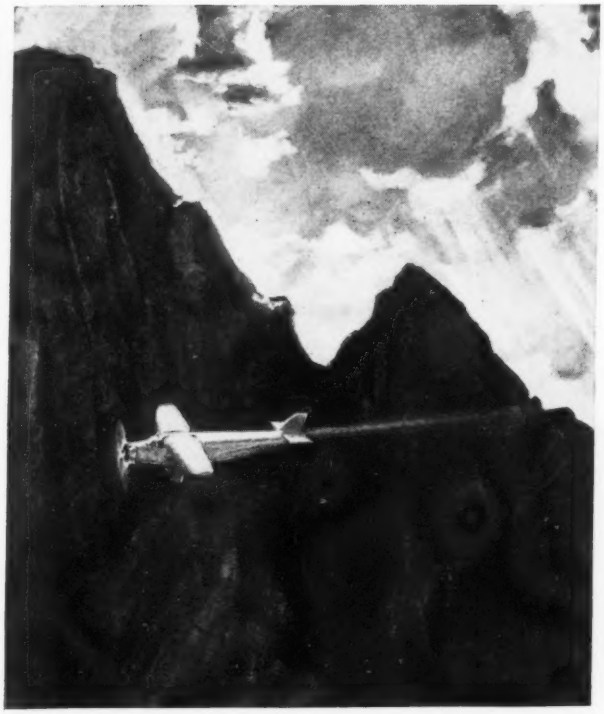

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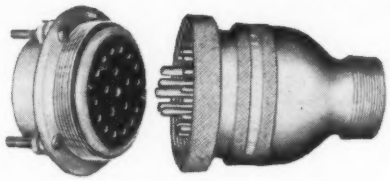

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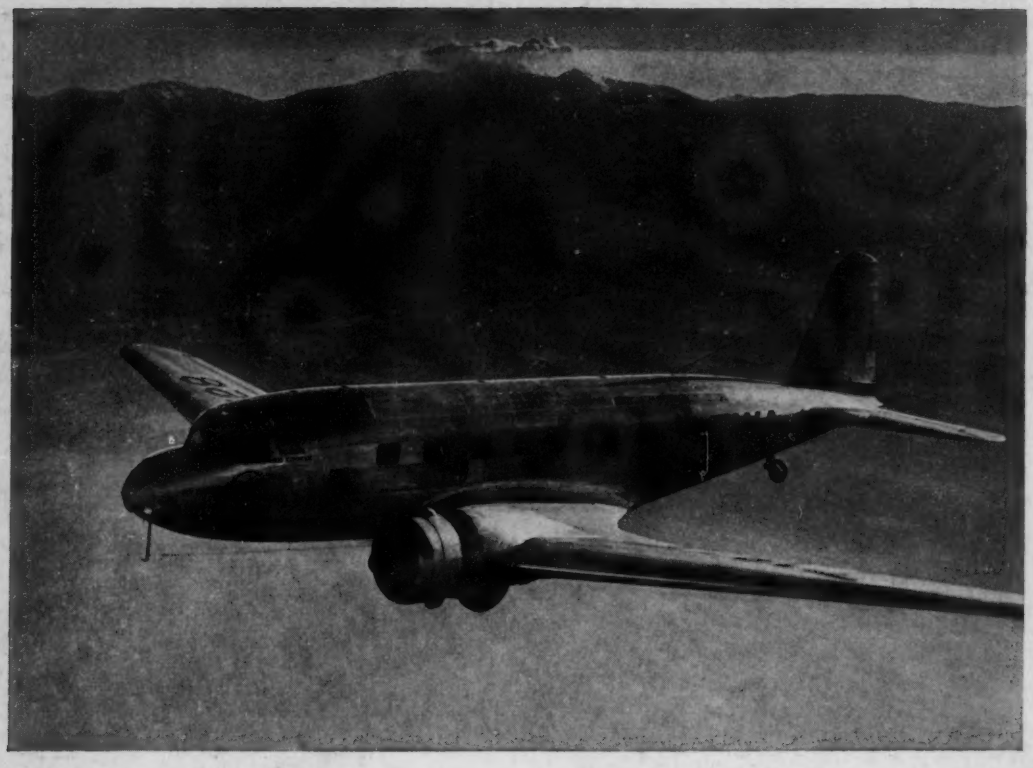

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